Aalto University
School of Chemical
Technology

School of Chemical Technology
Degree Programme of Bioproduct Technology

Yang Yang

Effect of changes in fibres' internal and external fibrillation on dewatering properties in paper making

Master's thesis for the degree of Master of Science in Technology submitted for inspection, Espoo, 20 August, 2014.

Supervisor **Professor Jouni Paltakari**

Instructor **Doctor Eero Hiltunen**

Aalto University
School of Chemical
Technology

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi

Abstract of master's thesis

Author Yang Yang	
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Abstract

The papermaking process can be described as a process to remove water from pulp. The purpose of this thesis is to evaluate the effects to dewatering properties in each sub-process including forming, pressing and drying.

Lampen mill refiner and Voith LR-40 refiner were used to generate 4 different types of pulp which were subject to dewatering with laboratory papermaking process. Moving belt former (MBF) is used to forming sheets and this machine also can generate different vacuum levels to remove the water from the wet web. Then the wet sheets are dewatered with MTS-press which can generate high pressure in a millisecond scale. IR-dryer is used to dry the sheets to evaluate the evaporation rate.

It is found that with the increasing energy level in refining, the heavily refined fibres are shorter, more fibrillation, straight and have more fines than that of lightly refined. Meanwhile, the Voith refined fibres have more fibrillation than Lampen refined pulp.

In forming part, the vacuum curves and surface level curves can be characterized by MBF. When high vacuum level was applied on wet web, the heavily refined pulps or high fines content furnishes have higher vacuum curves and longer drainage time because the fibrillations and more fines result in the web denser and less permeable. Voith refined samples have higher vacuum curves and longer drainage time than that of Lampen mill refined samples.

The dry solid content was measured after each sub-step. Heavily refined samples have lower dry solid content than that of lightly refined samples and Voith heavily refined samples have lower dry solid content than that of lampen heavily refined samples. The heavily refined pulps or more fines content have the lower speed to be dried. Lightly refined samples have higher evaporation rate than of heavily refined samples.

Keywords Fibrillation, Dewatering, Moving Belt Former(MBF), Vacuum level, MTS-press, IR-dryer, Dry Solid Content(DSC)

Foreword

This thesis was done at the laboratory of Department of Forest Products Technology in Aalto University from March to August in 2014.

I would like to thank my supervisor, Professor Jouni Paltakari and my instructor, Doctor Eero Hiltunen for their valuable comments and advices. Most importantly, by their guidance, I can have a clearly and right experiment direction. I am deeply grateful to them for helping me graduate in time.

I appreciate to all the people helping me during the experiment work. Especially, thanks to Tuyen Nguyen and Minna Mäenpää for teaching me the operation of MBF. They are very patiently to helping me solving problems with MBF as it was always does not work. Also, I appreciate to Christian Orassaari for the refining and the MTS pressing work. Their advices and friendship encourage me a lot.

Finally, I thanks to my parents who support me from a child to an adult. I also thanks to my fiancee to encourage me a lot when feel lonely in a foreign country.

Espoo. August 20, 2014

Yang Yang

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Contents

1. Introduction

The papermaking process can be describes as a process of remove water from pulp. The water in the fibre, its amount, distribution and behaviour has an important effect on dewatering efficiency and paper properties.

By using different refining methods and different energy level, pulps with different properties such as fine content and degree of fibrillation are obtained. Different pulps have different behaviours when forming the sheet and subject to pressing and drying which leads to the different properties of paper.

The target of this thesis is to evaluate the abilities of dewatering in each sub-precess. Papermaking is a complex process including refining, forming, drying etc. In terms of process condition and sheet structure, the paper made in the laboratory scale is not the same as a mill scale even though laboratory running the same processes as a mill scale. In order to eliminate the difference as much as possible the following equipment at the laboratory of Paper Technology in Aalto University are used and By using these equipment it can possibly create realistic conditions.

Lampen mill refined and Voith LR-40 refiner is used to generate 4 pulp types. Moving belt former is used to form the sheets and to dewater the sheets by vacuum. MTS- press is used to press wet sheet and determine the ability of dewatering by pressing. IR-drying is used to determine the water evaporate properties after press.

This thesis is divided into 4 parts. The first part is review literature about principles and theories of water-fibre interaction, forming, pressing, and drying. The second part is the experiment part including materials and methods. The third part presents result and discusss these phenomen. The last part makes conclusions to the whole thesis.

Part 1 Literature Review

2. Water-fibre interaction

Papermaking is a process which is essentially concerned with the separation of water from fibres. The water in the fibres, its amount, distribution and behaviour has an important effect on dewatering efficiency and paper properties.

Fibre and Water is liquid water present in the void spaces. Free water is not associated with the cell wall polymer and therefore does not affect the properties of paper.

Bound water is intimately associated with the cell wall polymers through hydrogen bonding with accessible hydroxyl (-OH) groups on the cell wall polymers.

Fibre saturation point is the point at which the bound water is at a maximum and no free water remains. And fibre saturation point is a concept as it is impossible to see or measure directly the point at which there is no free water and only bound water exists.

This part gives a brief introduction to the fibre-water interaction. During the process of papermaking the following phenomena will occurs on the paper machine, namely: the first stage is fibres swollen, then as the moisture content is decreased the fibre shrinkage occurs, finally with the removal of bound water by pressing and drying the hornification occurs.

2.1 Fibre Swelling

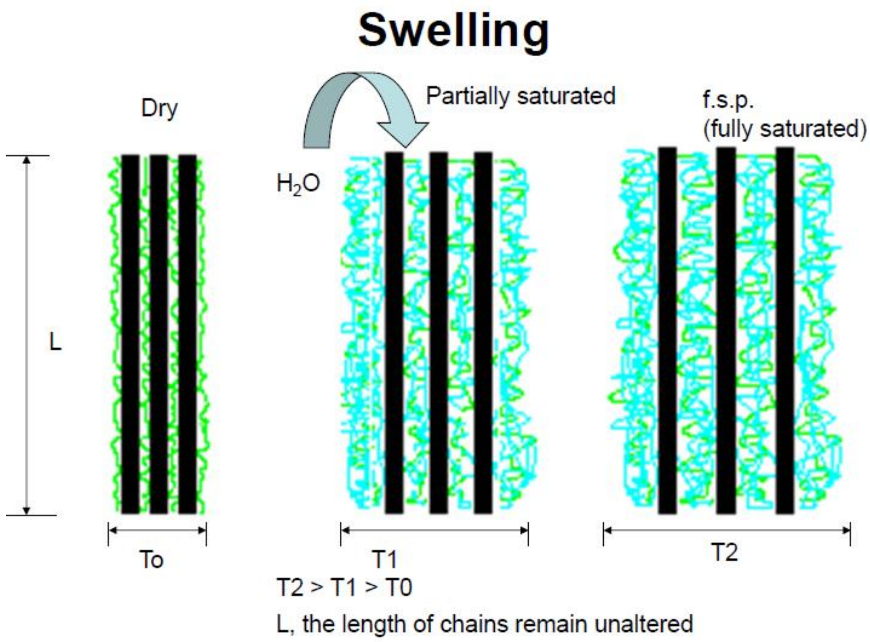

Figure 1. Fibre Swelling

A solid is said to swell when it takes up a liquid, whilst at the same time [**1**]

1. It does not lose its apparent homogeneity;
2. Its dimensions are enlarged
3. Its cohesion is diminished: instead of hard and brittle, it becomes soft and flexible.

Pulp fibres swell in water at their amorphous regions, which according to Katz's terminology is intermicellar swelling. Water molecules break the inter-molecular hydrogen bounds when they come into the amorphous regions of cellulose matrix. Thus, the chains of cellulose were increased, which is causing the swelling. Likewise, fibres shrink in a similar manner.

Water impregnated fibre can be seen as a polyelectrolyte gels, which is in equilibrium with the surrounding electrolyte solution. In the presence of water, part of the acid groups dissociates, releasing counter-ions X^+, which are held within the matrix of the gel to maintain electrical neutrality:

$$\mathrm{Gel} - \mathrm{COOX} = \mathrm{Gel} - \mathrm{COO}^- + \mathrm{X}^+$$

It is believed that the gel swells as a result of water entering in order to reduce the osmotic pressure [2]. This theory depends on the elasticity of the gel matrix, however cellulose is not a thermoplastic material but a hydroplastic material. Thus, the degree of swelling cannot be increased by heat [3].

In addition to gel swelling theory, the degree of swelling also can be increased by mechanical treatment and chemical treatment.

The structure of fibre cell wall after mechanical treatment like, beating or chemical treatment becomes softer so that it can attract more water. Thus, the interaction between water and cell wall polymers are generated and at the same time water also can displace some morphological units. The result of this phenomenon is that the thickness of fibre cell wall is increased and the width of fibre does not change.

The fibre cell wall consists of an interrupted lamellar structure of cellulose, lignin and hemicelluloses, where the fibril are packer more tightly in the radial direction the in the tangential direction [4]. Some amorphous material can be removed by pulping and lamellae, which can be very thick with large gaps in between them, is formed by microfibrils.

Scallan [5] suggested for a delignified cell wall a swelling mechanism, which is relying on the displacement of morphological unit. The cell wall is poreless when it is dry, after attracting water causes a cleavage of lamellae in the cell wall. Swelling caused cleavage of lamellae into a honeycomb pattern and finally a delamination. Therefore, the reason for swelling is due to the increasing volume between lamellae.

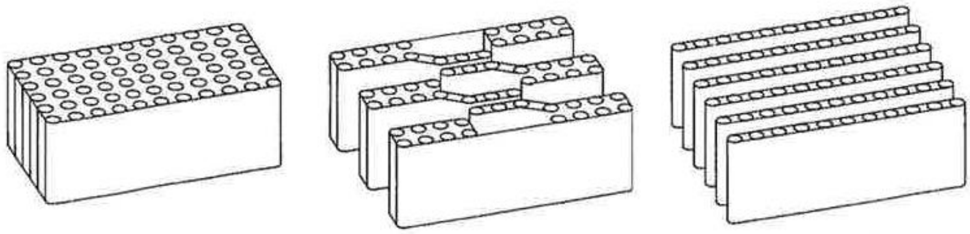

Figure 2. Fibre swelling model **[5]**

In conclusion, the following reasons contribute to the phenomenon of swelling [**6**]:

1. Water sorbed by hydroxyl groups and carboxylic acid groups;
2. Water taken up due to entropic effects when the polymers swell;
3. Swelling water due to the osmotic pressure created by releasing ions;
4. Water held in pores by capillary pressure.

2.2 Fibre Shrinkage

Fibre shrinkage is unavoidably caused by water removal. Fibre shrinkage is somehow connected to web shrinkage as well as to the internal web tension; therefore it is important to understand the fibre shrinkage processes. It has been proposed that fibre shrinkage occurs in two phases **[**6**]**:

Phase 1:

Shrinkage is caused by the dewatering of large intra-fibre cell wall pores. As a result, the voids between the tangentially oriented, interrupted, lamellar structure elements collapse. Shape changes in the fibre cross-section are caused by intra- and inter- fibre capillary forces acting on the fibre cell wall. The removal of pore water causes mainly tangentially oriented, inter-lamellar pores to close or to tighten; this causes shrinkage orthogonal to the lamella plane. This means that the fibre tends to flatten rather than to shrink in the direction of the fibre width. Shrinkage is assumed to start when the fibre saturation point in drying is exceeded.

Phase 2:

Shrinkage starts in the final phase of drying, when the tightly bound water leaves the fibre micro-structure. At this stage, the non-freezing water fraction is removed. Cell wall pores have closed already and the remaining water situated in the non-crystalline domains **[**7**]**. The removal of this water causes the observed late shrinkage in the direction of fibre width. Shrinkage at phase 2 starts in a moisture range where the morphological features do not seem to matter.

Therefore, we can conclude that in 1st phase shrinkage depends on morphology, while the 2nd phase is morphology-independent. Shrinkage in 1st phase is caused by collapse of gaps between the lamellae structure. When remove the bound water in the lamellae, the 2nd phase occurs. The last part of water removal occurs in air drying and only some water directly bonded to the cellulose molecule remains. However, this directly bonded water does not affect the dimension of fibre. The progress of the fibre wall shrinkage is shown in Figure 3.

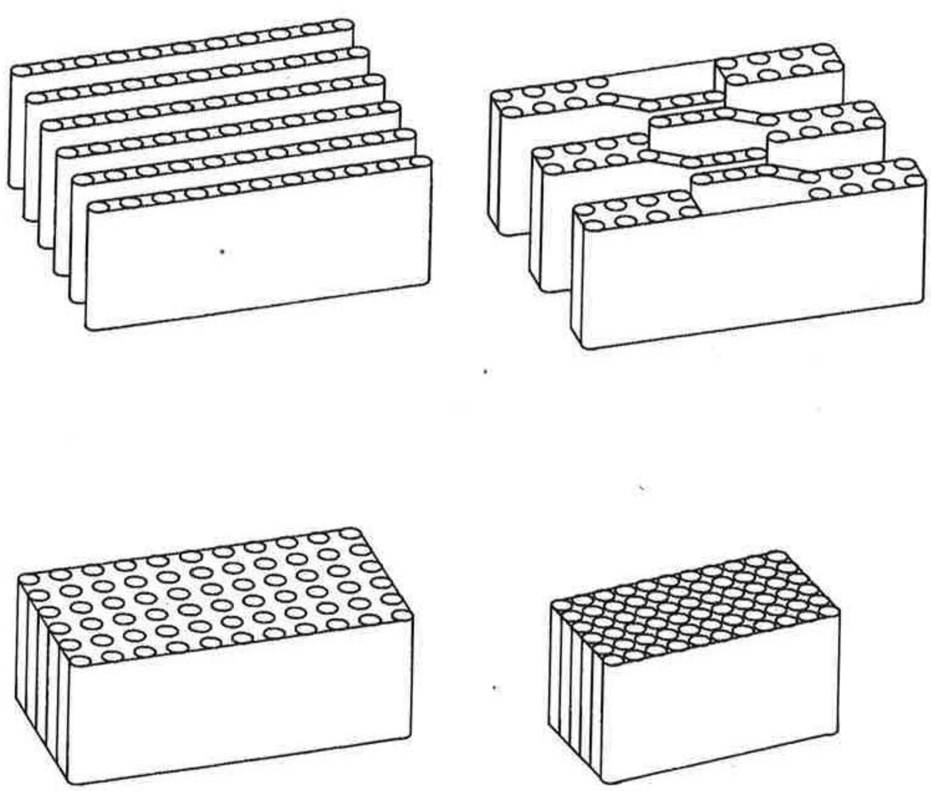

Figure 3. Fibre wall shrinkage model developed from the inverse of Scallan's fibre swelling model [6].

2.3 Hornification

When a low-yield pulp is dried and rewetted there is a loss of swelling which is known as hornification. The term hornification is used to describe structure changes in fibres occurring in fibre drying or recycling. Hornification is a pulp property, which is closely to the properties of single fibre. Hornification can be divided into two distinct phases: wet and dry hornification.

For many pulps wet hornification was usually found to occur in a range of 40-70% solids content. The morphology of the fibre plays an important role in wet hornification. Removing the water causes the cell wall to contract and pores to close. Hence, the water-filled structure seems to be restrained from collapsing until water is removed, either due to sufficient resistance by the structure resistance by the structure itself or some other reason. Due to the morphological restraints in the cell wall, wet hornification stops at a certain point.

By contrast, dry hornification is not indicated by changes in the microscopic morphology. As in paper aging, change take place at the molecular level and do not affect the morphology appearance of the fibre cell. Heat increases the irreversibility of the de-swelling and hence, supports an increase in hornification.

2.4 Bound Water

Bound water exists in any hygroscopic porous material, and water molecules can form hydrogen bounds with free hydroxyls which held by cellulose and hemicellulose. In addition to that, water also exists in amorphous part which is close to the bound groups. As there are some pores in the fibre cell wall, the water also retain in this region.

When water absorb on the surface, the water molecules can form monolayer or multi-molecules layers. Due to close the surface, the first layer of water molecules cannot easily moved. Thus, the molecules far from the surface can move more freely [8]. Water can diffuse in these layers and the driving force is the different concentration of bound water or a simply moisture gradient in the hygroscopic region.

3. Forming

3.1 Forming and dewatering at wire section of a Fourdrinier machine

The stock, containing various fibres, fines and chemical additives, passes through a number of high-shear devices into a headbox where the stock mixed with short circulation. In order to break the fibre networks, turbulence must be generated in it and to distribute the flow through the slice. Then the jet impinges on the wire where drainage starts immediately. The angle of jet impingement, the speed difference between jet and wire and the amount of turbulence in the stock will all have important effects on how the stock will drainage on the wire. There are many factors influencing the drainage, such as the geometry of the wire and the interaction of the fibres.

In wed forming on an open wire section, as on a Fourdriner type former, the first table element is usually the forming board, which helps reduce excess initial drainage. The next table elements are either foils or table rolls, depending on the speed and design of the machine. Foils produce a small initial pressure pulse followed by steadily increasing vacuum over the width of the foil. Table rolls produce a strong initial pressure pulse which increases rapidly with the speed of the machine, followed by a vacuum pulse. As soon as the initial layer of the fibre mat is formed, this considerably impedes drainage. However, the pressure pulse from the table rolls and foils disrupt the mat which then re-disperses, effectively raising the stock consistency. This mechanism is known as turbulent thickening. At some point on the table a mat is formed and the remaining slurry is drained through this mat. The mechanism of turbulent is more important toward the headbox, while filtration dominates as one move toward the couch.

As the web moves down the table, a point is reached where further water removal compresses the mat and surface gloss is reduced sharply. This point is readily seen on a Fourdrinier and is known as the wet line. The dry line occurs at some point after the wet line when air starts to flow through the web 1/2. Beginning at the wet line, surface tension and other interfacial phenomena become important.

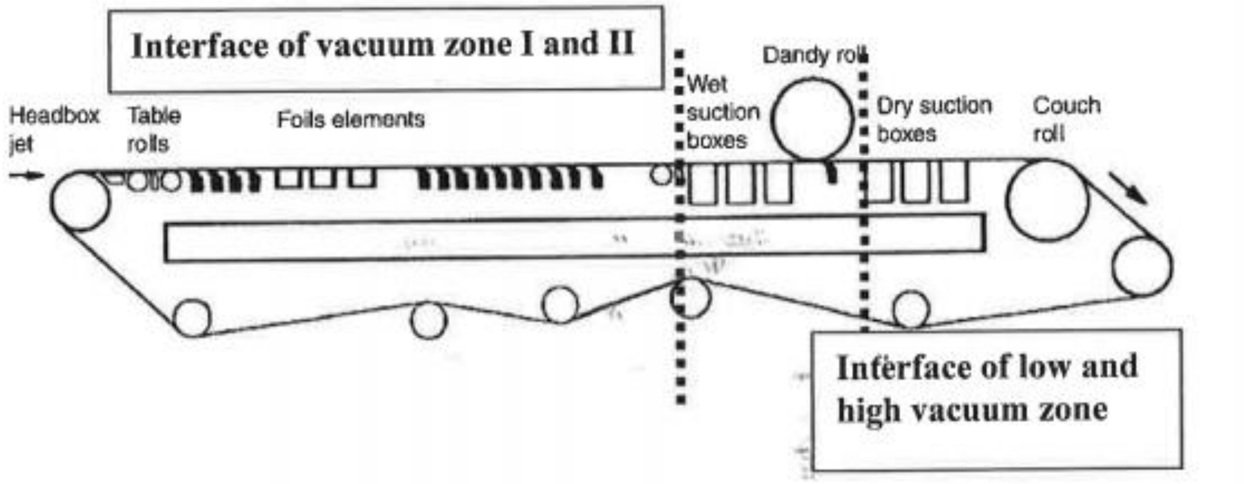

Figure 4. The water line in the forming section in a Fourdrinier machine

The process of dewatering on a paper machine is generally divided into two stages. Stage I starts from the headbox slice and ends at the leading edge of the first suction box. The rest of the wire section, including the couch roll is called Zone II. Zone I therefore deals with the formation of the wed and the drainage of the stock under a turbulent thickening and then filtration mechanism, while Zone II deals with the dewatering by vacuum. The vacuum zone can be further divided into low- and high- vacuum zone. The suction levels of low vacuum zones are 2 to 15 kPa, and the dry solids content after this part is in the range 4-7%. From these solids content to the wire section higher vacuum levels at the needed make the web dry and strong enough to endure the dewatering by the press suction. In this stage, flat boxes, also called dry suction boxes, and couch rolls are utilized. After the wire section the solid content of the web is usually from 15% to 23%.

3.2 Effects of process variables on dewatering in the wire section

During the process of vacuum dewatering, the main factors are suction time, vacuum degree and temperature distribution in the pulp. The method to calculate the effective suction time is that dividing the MD width of suction box by the machine speed.

The beginning part of dry solid content with suction time curve is a type of exponential curve like Figure 5. In this part the dry solid content depends mainly on basis weight. At the same time, different types of furnishes with different freeness number more or less affect the result.

In addition to that, the vacuum level also can affect the dewatering. The higher vacuum level, the more water being removed which means the drier web. However, the relation between dewatering and vacuum level is not linear or similar for all furnishes. Comparing the light basis weight and heavy basis weight sheet, the lighter basis weight can achieve the final solid content faster. However, giving enough time for a heavy basis weight structure, the heavier sheet becomes dryer.

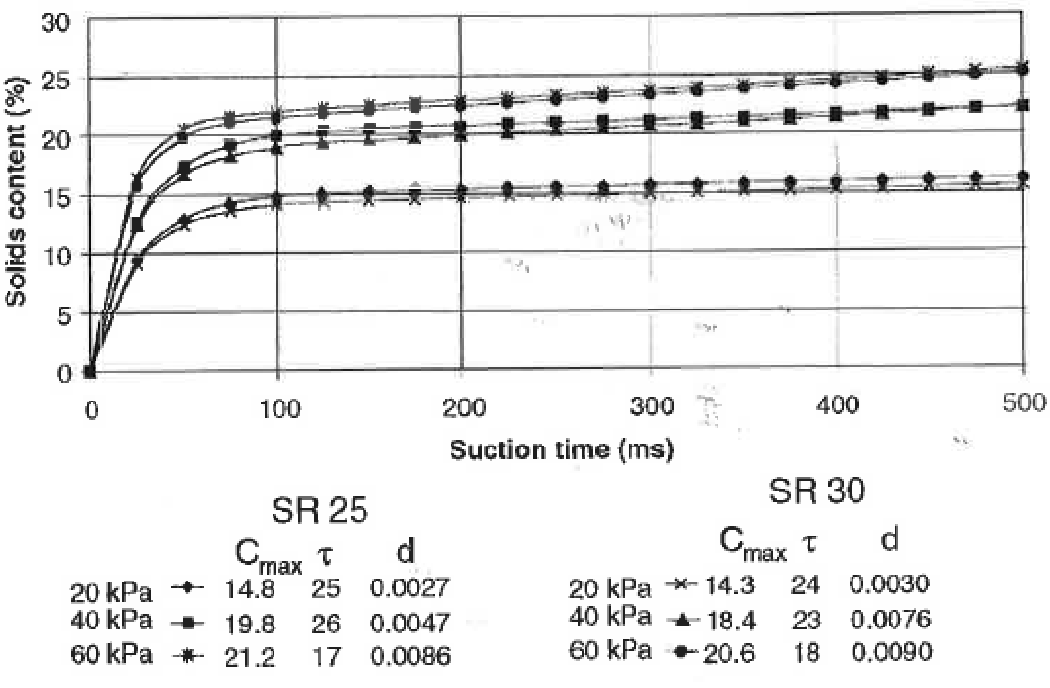

Figure 5. Dewatering curves for fine paper furnishes [8].

3.3 Effects of paper and board grade on dewatering tested by MBF

In this thesis, moving belt forming is used to forming sheet and detecting the dewatering. The following equation is used to describe the water removal behaviour of furnishes:

$$C = C_0 + b\left(1 - e^{-\frac{t}{\tau}}\right) + d \cdot t$$

Where C is the solid content of the fibre mat at the vacuum level in question after effective suction time t and

C_0 is the initial solid content before applying vacuum level above 10 kPa

b shows the maximum solids content rise obtained without the effect of throw-flow of air

τ describes the time needed to reach a change equal to 63% of b, while d=0

d indicates the long term effect of the through flow of air.

Various paper and board grades have different furnish compositions and grammages. The properties such as the freeness value, the degree of fibrillation and the water retention value are not the same. Thus, different properties of furnish result in different degree of dewatering.

The more fines the furnish contains, the lower the freeness value. Vacuum dewatering does not depends on the freeness-values or the amount of fines, although a linear correlation has been shown between vacuum dewatering and these variables. The best dewatering is obtained when the web is suitably consolidated due to fines and hence responds better to the suction flow, which in turn results in a higher vacuum level and compression of the web. If the fines content is higher than in the optimal case, the increased swelling and surface area outweigh the effect of increased vacuum, and the dewatering diminishes.

The maximum obtained solids content under constant vacuum dewatering conditions has been found to increase up to a certain grammage, but then the maximum solids content starts to decrease. The lighter grammage have also been found achieve the final solids content faster. Even though at the beginning the lighter sheets are drier, given enough time, the heavier sheet becomes dryer.

Fine paper furnishes were used to describe the behaviour of chemical pulp furnishes in vacuum dewatering [9]. The component of fine paper furnishes are usually 30-40% of bleached softwood kraft pulp and 60-70% bleached hardwood kraft pulp with SR 25-30.

The dewatering curves depending on different furnish types with numerical parameters are shown in Figure 5. It can be clearly seen that the difference of dewatering curves with different beating degree is slightly. Although the obtained solids content gives as Cmax follows the freeness value systematically and the differences are small between these furnishes [8]. It is obviously that the higher vacuum level, the higher dry solid content.

Mechanical pulp contains more fines and more stiff than that in chemical pulp. The web from mechanical pulp is less compressible and bulkier than that from chemical pulp. The dewatering curves of different mechanical pulp used for news print are shown in Figure 6. We can see that among the mechanical pulp in two vacuum level cases TMP reach the highest solid content. It can be clearly seen that in low vacuum level at 20kPa these three types of furnishes reach the same dry solid content, but the TMP reach fastest than the other two types. However, in high vacuum level at 50kPa, these three type furnishes have the same time, but different degree of dry solid content and the TMP obtain the highest the dry solid content.

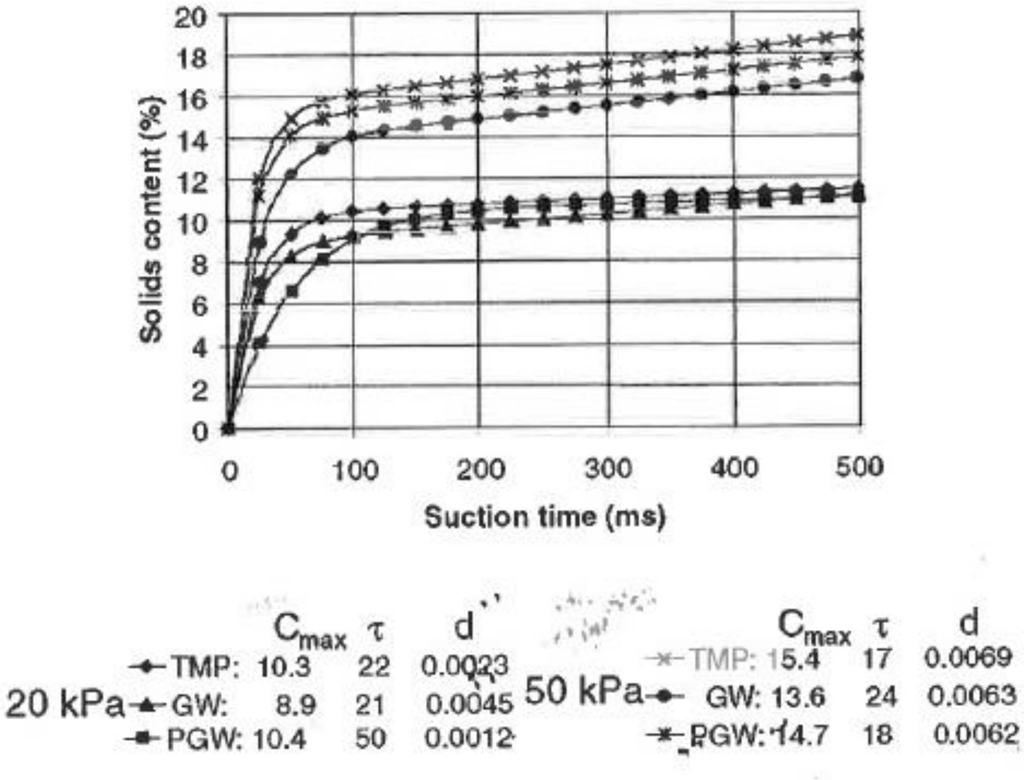

Figure 6. Dewatering curves of news print furnishes at vacuum level [8].

SC and LWC paper have lower dry solid content than that of chemical pulp due to the component of SC and LWC paper are mainly mechanical pulp. The dewatering curves of SC and LWC furnishes are shown in Figure 7 and Figure 8 [9].

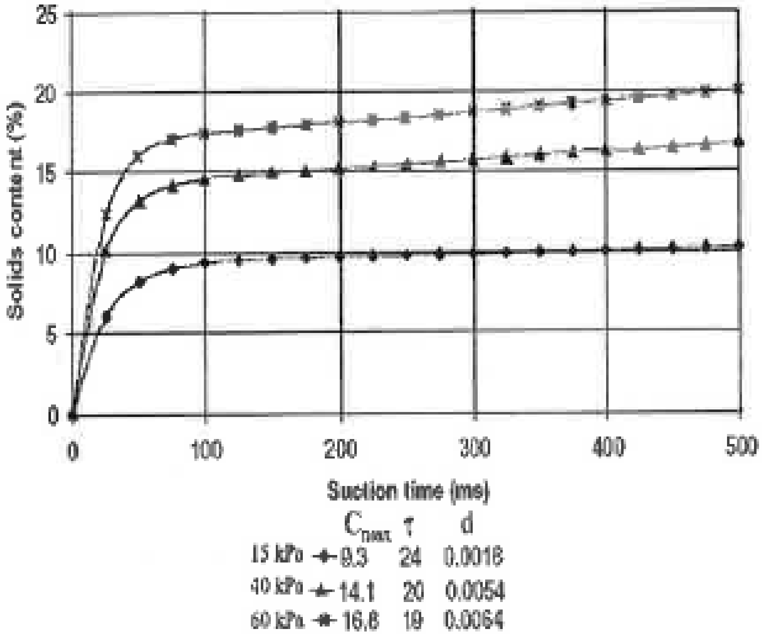

Figure 7. Dewatering curves of SC grade furnishes [9].

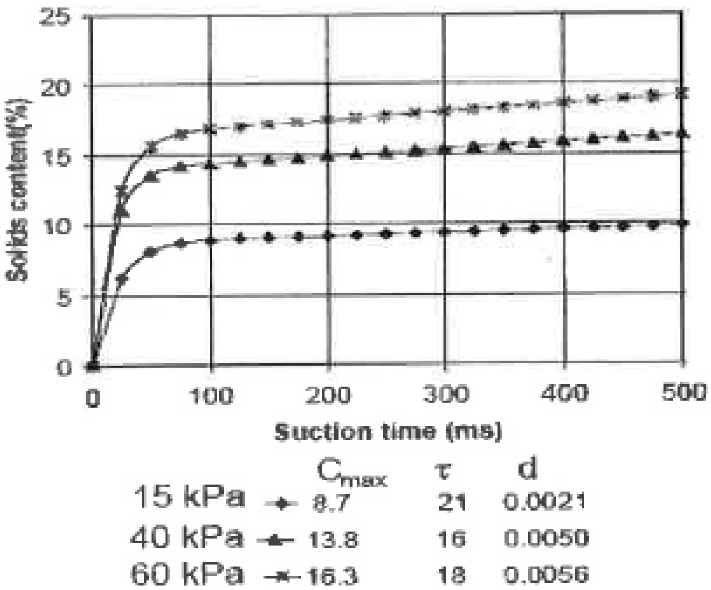

Figure 8. Dewatering curves of LWC grade furnishes [9].

It can be clearly seen that compared to the fine paper furnishes the maximum dry solid content of SC and LWC furnishes are much lower. Even though increasing the vacuum level the maximum dry solid content is still lower than that of fine paper furnishes.

In order to obtain a higher dry solid content, relatively suction time and higher vacuum level are needed. It means that the consumption of energy in wire wear and cool the web is increased. At the same the dewatering potential in the following dewatering elements is reduced. If the excess vacuum level is applied in too early position in the wire suction, so-called sheet and pin holes may occur.

3.4 Effect of machine speed and foils on dewatering and retention

In a paper machine wire section the setting of foil distribution and their angles affect activity in turn affects dewatering, formation and retention by exerting both positive and negative pressure pulses on the forming web.

Foil element consists of a fixed blade assembly at the bottom of the wire, and it formed a small expansion angle with the wire and conductor, generating an under-pressure. By selecting a small enough angel, however, sometimes less than 1 degree, can obtain a suitable suction pressure even under high line speed generated. Much of the water sucked down by a foil element will cling to the wire underside and be doctored off by the next foil element. If the leading edge of metal foil components is too sharp, the service life of wire will be reduced. A small amount of water is pressed back through the wire when the pressure pulse generated by the front page. However, more water is pressed back through the wire in the following table roll case.

The structure evolved during this forming stage also contributes to the dewatering on flat boxes and couch roll. The coarser bottom layer of the web allows water to flow through easier than the denser layer. It has been found that better retention also results in a more uniform distribution of fillers in z-direction. This may also be understood so that with poorer retention the fillers and fines are more thoroughly washed off from the bottom side of the web. The experiments in which different pulsation rates were used and retention and dewatering were measured showed that a higher pulsation rate impaired retention whilst, in some cases, improving dewatering. Dewatering on flatboxes and couch rolls is mainly carried out by compression due to the pressure difference but also on the viscoelastic properties of the wet fibre mat. This means that both pressing time and relaxation of the fibre mat have to be taken into account. The test series was carried out in which both pressure and pulsation rate were varied. By changing the belt speed, both the duration of individual suction pulses and the relaxation time between pulses changed. Results showed [9] that increasing the pulsation rate does not alone improving dewatering, but the vacuum level has to be suitable for the pulsation rate used.

4. Pressing

4.1 Mechanism of wet pressing

The final density of paper is determined in wet pressing part. Thus wet pressing in more important in paper properties. After wet pressing the thickness of wet sheet is decreased, thus, the average density is increased.

The mechanisms in wet pressing are as the following [8]:

1. The fibres are flattened and brought closer together; improving bond. This contributes to a permanent densification and improves bonding
2. The water flow creating viscous drag makes network material movement. The flow velocity increases in the direction of the flow, which means that the compression pressure also increases. The compression pressure causes a permanent z-direction density gradient in the web.
3. The network bonds are not well developed yet, thus, the water flow can separate particles from each other and move the particles to new position or move the particle out of the network.

4. During the wet pressing the web is still plastic state, therefore, the pressing the web against surface of a roll or press felt results in topographical change, which means the two sidedness.

Nilsson and Larsson [10] analysed so-called transversal flow type press nip. According to their analysis, the characteristics feature of such a nip is that the hydraulic pressure build-up in the felt is very low and at least in the first part approximation, can be regarded as the zero pressure level for the hydraulic pressure in the paper web.

The nip was divided into four phases:

Phase 1 – From this point the pressure curve rises until the paper web has become saturated. Before this, no hydraulic pressure will develop. The total pressure of the sheet starts to grow but no water actually flows until the saturation point has been reached. This means that no hydraulic pressure will be built up and the total pressure equals structure pressure.

Phase 2 – From the saturation of the web starts to the mid nip, or more accurately to the maximum point of the nip pressure curve. The water starts to leave the sheet and a hydraulic pressure starts to increase. The fibre structural pressure is increasing as long as the dryness of the sheet is increasing.

Phase 3 – From the maximum point of the nip curve to the maximum dryness point. The total pressure decreases and the fibre structural pressure increasing to a maximum point where the maximum dryness in the nip corresponding.

Phase 4 – Rewetting phase, where the paper starts to expand, and water enters the sheet and continues until felt and paper are separated. The hydraulic pressure will change to negative and water flows to opposite direction of phase 2 and 3. In this area the fibre structural pressure is greater than the total pressure. But during this area water is sucked into the fibre so called rewetting phenomenon is occurring. However, the rewetting is still controversial issue.

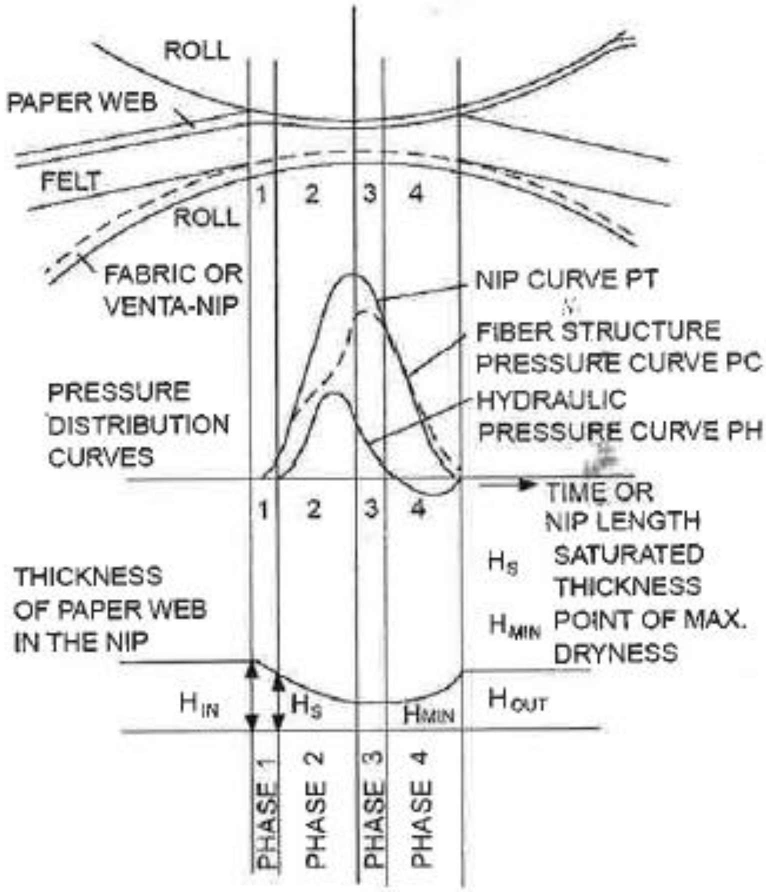

Figure 10. The four phases of the nip process [10].

The magnitude of hydraulic pressure is affected by refining of pulp, the amount of fines, basis weight and compression rate. If the initial moisture content of the web is high and the compression speed is fast like at the first press in a high speed machine, the high hydraulic pressure will occur on the side of web made of refined pulp in contact with the roll regardless of low basis weight (e.g., at 50g/m^2). As the compactness of web increases the role of hydraulic pressure is gradually diminished. On the other hand, the role of the structural pressure increases in balancing the compression forces. The water within the material contributes to the compression force decisively. Mechanical stiffness of the web is characteristic in the final stage of the wet pressing because the magnitude of structural pressure in the wet pressing is becomes higher as the wet pressing is progressing.

4.2 The process variables of wet pressing

There are many factors affecting the results of wet pressing and these factors can be sorted into two types: equipment variables and process variables. However, only one device, named MTS-press, was used in this study, thus, the equipment variables will not be involved. The process variables include nip pressure, temperature, nip residence time moisture content of wet sheet and sheet properties.

The nip type of wet pressing can be categorized into pressure controlled nip and flow controlled nip based on the water removal behaviour. During the pressure controlled pressing the dryness is mainly determined by the moisture ratio at mid nip pressure. The increasing moisture ratio is due to the flow resistance in the fibre wall rather than in the paper structure. The water retention value (WRV) can approximate the obtainable the wet pressing ability in the pressure controlled nip it is favoured to increase pressure rather than increase dwell time, for example, pressing ground wood papers, tissue, toweling and lightweight fine papers within the normal time frame. Generally, the pressing of heavy weight grades or sheets having high drainage resistance form flow controlled nips. Also high moisture content of web can lead to a flow controlled nip. However, the pressing of lightweight grades or sheet having low drainage resistance form pressure controlled nip.

In addition to that, web temperature is also playing an important role in water removal at pressing stage. With the increasing web temperature, water viscosity and water surface tension are decreased and fibres become more softness. According to Royo and Thorp's research [11], when the temperature increased from 37.8 to 82℃, the viscosity can reduce 50%. At the same time, the dry solid content also can be increased.

Moreover, higher ingoing moisture content of web results in higher outgoing moisture content in the wet pressing. Due to that, the hydraulic pressure in the web will be increased and if the content exceed, sheet maybe crush in the first nip.

The different properties of furnishes, including amount of fibrillation and fines, the degree of swelling etc, also is another important factor affect the result of pressing. According to Allan's research water removal corresponeded to the amount of water held among fibres in first press performance. However, sheet formation and fibre length shows no effect on it and fines play more important role than fibrillation. They also did more research on factors, such as degree of refining, fibre length, fibre fibrillation, to wet pressing by using cotton fibre and UBK [12]:

1. Sheet formation: has no influence on either the percent dryness achieved or the dryness change within the press nip under the press condition examined
2. Fibre length: classified by Bauer McNett classifier, fibre length did not affect either the dryness by pressing or the change in the dryness of the sheets within the nip
3. Degree of refining: the sheet formed with unbeaten fibres exhibits a relatively stronger expansion after the mid nip than the sheet from beaten fibres. More rerfined fibre by PFI mill showed lower sheet dryness
4. Fibre fibrillation: fibre refined by PFI mill and without fines tested, the more refining resulted in lower solid content
5. Fibre swelling: 65% of zinc chloride used as a swelling agent and the treatment with zinc chloride decreased the dry solid content

5. Drying

In each sub-process of a paper machine the consistency of stock are not the same in order to apply the equipment and obtain certain sheet properties. Headbox is the beginning of a paper machine and the consistency of stock here is 0.2 - 1.0%. Under the effect of gravitation, pulsation and vacuum water removal in the forming part, the consistency of stock is 15 – 25%. The following sub-process is wet pressing using mechanical effect and the consistency of web increases to 33 – 55%. After that, wet web is translated to dry section where water is evaporated by heating. Finally, after drying, the web only contains 5-9% water which cannot easily be removed.

In light of energy consumption, the web is desired to removal as much water as possible before going to the dry section. In order to removal water, the dry section should provide very high temperature thus the energy consumption is high. Compare with drainage in wire section and press section, huge energy consumption in dry section leads to more expensive. However, by the limitation of mechanical and press technology, there are restrictions to increasing the dryness.

Regardless of the drying method, the drying processes have to have following basis requirements [13]:

- Drying capacity: design of a drying section must be able to use maximum evaporation capacity per dryer unit for all paper grades produced.
- Evaporation profiles: the variation of evaporation profile of paper in cross direction is vital because the variation causes the paper property variation and runnability problems.
- Runnability of dryer section: the runnability of dryer is directly related to machine efficiency, thus, the web break must be prevented.
- Good energy economy: design of the dryer section and associate components such as steam, condensate, and ventilation system should minimize energy consumption.

The water inside fibre wall can be divided into three fractions: bulk water, free water and bound water which are composed of freezing bound water and non-freezing bound water. During drying process, the first phase is heating period. In this period, the temperature of cylinders is not very high in order to prevent sticking of the web on the cylinders. The next phase is constant rate period where most of free water is removed. After drying of free water, the web has a certain degree of dryness called critical moisture content. Thus, after this period, the moisture content reaches this point. The last phase of drying process is the falling rate period

5.1 Various drying methods

Nowadays, by the limitation of technology, the drying method is dominated by steam heated multi cylinder. In order to increasing the drying efficiency and functional properties and reducing the energy consumption, some new dry ways are still under research.

The following are commercial and developing drying method [14]

- Multicylinder drying: printing paper and boards
- Yankee cylinder drying: soft tissues, boards, machine glazed paper.
- Through drying: soft tissues, fibre and filter fabrics
- Airborne drying or nozzle drying: no-contact drying or coated and surface-sized paper, unrestrained drying of kraft sack paper, drying of market pulp
- Infrared drying (electronic or gas): drying in surface sizing and coating, web handling, moisture profile control
- Condebelt: in production scale, primarily board (liner and fluting), provides board property improvements unattainable with traditional cylinder drying
- Impingement drying (hoods located on the paper machine drying section and placed against the web supported by a drying cylinder, roll or fabric): increasing drying capacity, drying of coated board, unrestrained drying of kraft sack paper
- Induction drying: moisture profile control
- Microwave drying: pilot scale, moisture profile control
- Impulse drying: pilot scale
- Press drying: pilot stage
- Drying with superheated steam: pilot stage.

5.2 Shrinkage of Paper

It is inevitable that paper shrinkage occurs during drying process. The shrinkage directions are both thickness direction and plane direction of paper web. The paper web mainly shrinks in CD (cross direction) rather than in MD (machine direction). The reason is that the paper web is restrained in MD. The middle of paper web shrinks less than the edge. Due to the uneven shrinkage, the properties of paper web are not the same in cross direction.

Shrinkage in plane usually starts after removal of most free inter-fibre water, thus the surface tension is the main force for shrinkage. The geometry, degree of beaten and degree of fibrillation affect the dryness point where paper web starts to shrink. The paper web of beaten pulp starts shrink at 20 – 30% dryness, while for unbeaten pulp the point range is 40 - 50%. The reason is that beaten pulp has more swelling which result in more water existing in the fibre rather than stay between fibres. The inter-fibre water evaporates at lower solid content for beaten pulp.

With the decreasing moisture content of paper web, single fibre starts to shrink and form fibre to fibre bond [13]. The most important factors affecting fibre shrinkage are the content of hemicellulose and drying history. Generally, the more swell, the more shrinkage. More hemicellulose can increase the degree of swelling. By contrast, recycling fibres are not easily to swelling which leads to lower shrinkage.

Part 2 Experiments

6. Experimental Part

6.1 Objectives

The target of the thesis was to analysis differently refined pulp samples with different properties and their dewatering properties with a laboratory simulation which is close to real papermaking mill such as Moving Belt Former, MTS-pressing and thermogravimetric balance system.

By using different refining methods and different energy level, pulps with different properties such as fines content and degree of fibrillation are obtained. Different pulps have different behaviours when forming the sheet and subject to pressing and drying which leads to the different properties of paper.

6.2 Materials

In this work softwood (pine + spruce) and hardwood kraft pulp were used. The pulp was refined with different refiner and energy level.

In this experiment, samples were categorized in 4 types. Hardwood was refined by Lampen mill and Voith LR-40 refiner with the different energy intensive. Softwood was refined with Voith LR-40 refiner under a certain energy level. After refining, hardwood and softwood fibres were mixed with a ratio 80% : 20%.

	Revolution	Refining Consistency (%)	SR°
Lampen lightly refined	3500	3	17
Lampen heavily refined	7000	3	21

Table 1. Refining condition with Lampen mill refiner

	Specific Refining Energy(kWh/t)	Refining Consistency (%)	SR°	Specific edge load(J/m)
Voith lightly refined	75	4	34,4	0,60
Voith heavily refined	150	4	58	0,60

Table 2. Refining condition with Voith LR-40 refiner

6.3 Experimental devices

Bleached softwood and hardwood pulp were refined and making sheets and dewatering. The following devices are used for the experiment.

- **Lampén mill**: This refiner is quite a silent machine during the operation. The Lampén mill refiner is consisted with a ball housing with drive, cover, frame and 10 kg metal ball. The ball beats the pulp in the ball housing with rotates speed at 250 rev/min. The Lampen mill is shown in the Figure 9.

Figure 9. Lampén mill refiner.

- **Voith LR-40 refiner:** This machine is a smaller laboratory scale refiner compared with industrial refiner which is able to control refining energy in mill scale. This refiner eliminates the differences between laboratory and mill scale. The Voith LR-40 refiner is shown in the Figure 10.

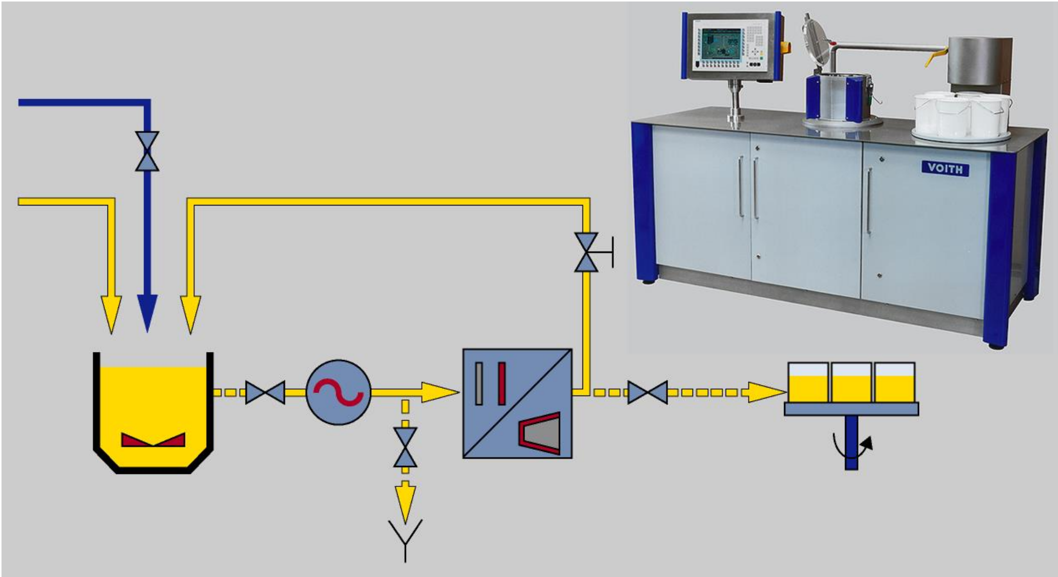

Figure 10. Voith LR-40 refiner.

- **Moving Belt Former (MBF):** This former is designed for vacuum dewatering and surface level research. The low vacuum and very high vacuum can be used in this machine. The grooved belt with holes is located under the forming wire and on the suction box. The difference between industrial mills was that the forming wire does not move, but the belt moves. The speed difference between belt and wire is comparable to Fourdrinier machine. The operation step is pouring the pulp into mix chamber and the mixed time can be changed according to the need. The closing plastic sheet prevents the leakage of pulp from the mix chamber. After mixing, firstly the closing plastic sheet is pulled out, and then the pulp enters the former chamber. At the same time, the belt start to moving around and the suction starts with a certain vacuum. The data of vacuum level and surface level can be recorded by the computer. The sheet size formed by MBF is 165mm x 165mm. The Moving Belt Former is shown in the Figure 11 and Figure 12.

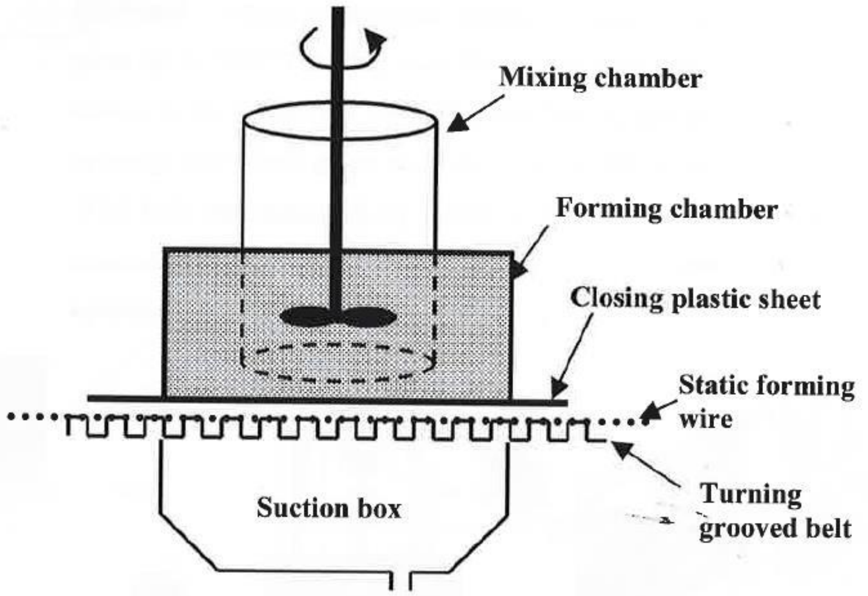

Figure 11. The scheme of the Moving Belt Former.

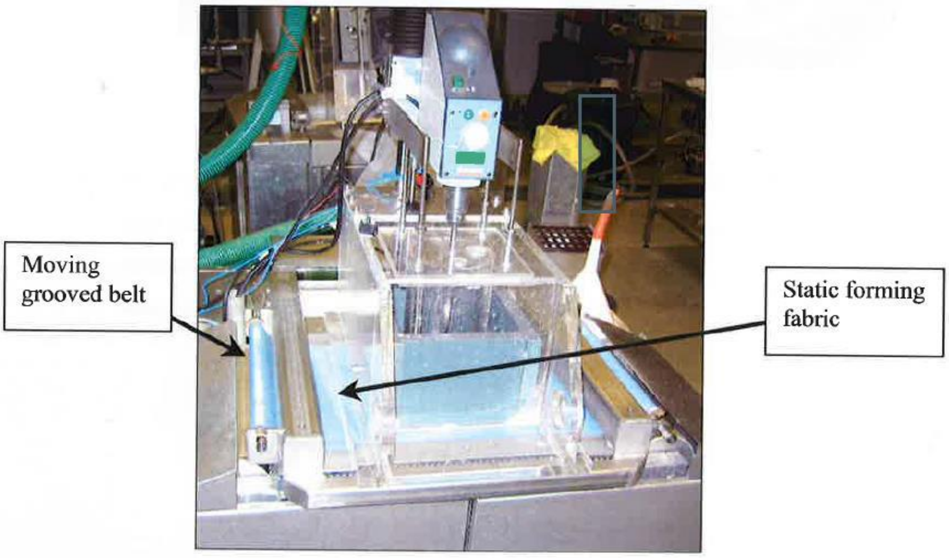

Figure 12. Moving Belt Former in Puu laboratory.

- **MTS-press:** The MTS-press can generate a high pressure in a short time between top and bottom plate. The pressure and residence time can be changed by the computer. A pulse curve is recorded during the pressing and can be analysed after pressing. The MTS-810 press is shown in the Figure 13.

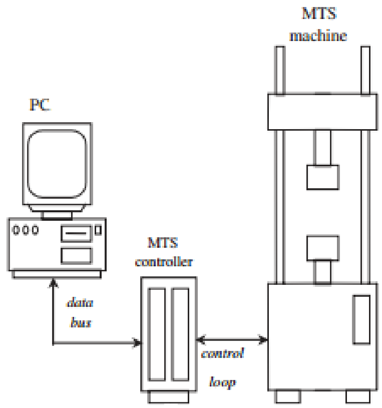

Figure 13. MTS-810 Press.

- **IR-dryer:** IR moisture dryer can heat the sample to 185 °c and the drying properties can be got, such as the evaporation rate, moisture content, etc. The IR-dryer is shown in the figure.

Figure 14. The IR-dryer with a data collection computer.

6.4 Experiment process

6.4.1 Refining

Pulp was refined with Lampen mill refiner at 3500 and 7000 revolutions respectively. The maximum weight in the housing is 30g oven dry.

Pulp was refined by Voith LR-40 at 75 and 150 KWh/t respectively. The maximum weight is 1200g oven dry.

6.4.2 Dry solid content evaluate

After refining with Voith LR-40 refiner and Lampen mill refiner, pulp was used to form sheets with Moving Belt Former (MBF) under low and high vacuum. The target of this experiment part is to evaluate the different dry solid content under different vacuum condition. The scheme of this experiment part is as following.

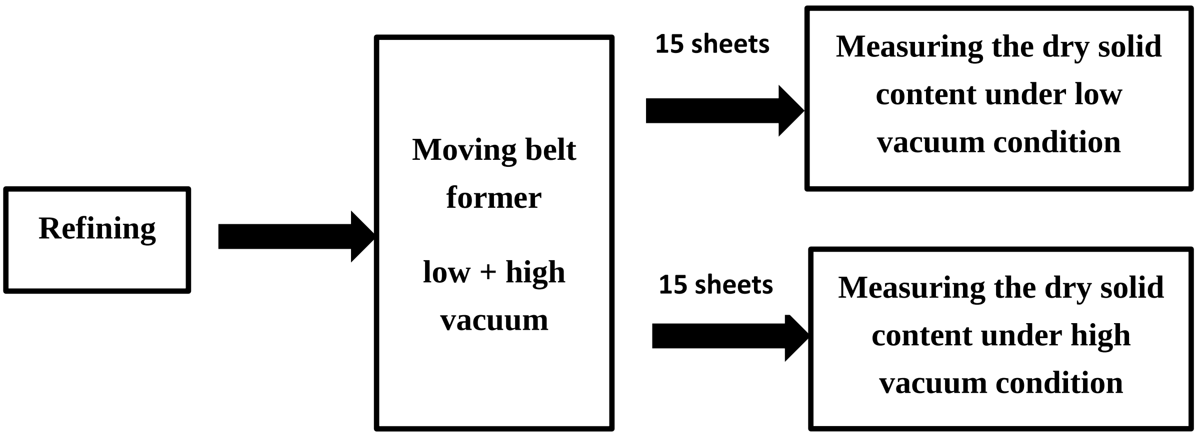

Figure 15. The scheme of evaluation the dry solids content after MBF forming.

15 sheets were formed both under the low and high vacuum condition. Every formed wet sheet was put into a rapid dryer after measuring wet weight in order to measure the dry solid content after forming.

The forming consistency of pulp with MBF is 3g/L.

- Mixing speed and time : 1350 rpm and 45 seconds
- low and high vacuum applying time: 400ms and 500ms
- Pulsation: 75Hz
- Grooved belt speed: 6m/s

6.4.3 Evaluation of dewatering properties

The target of this experiment part is to evaluate the drying properties of different fibrillated pulps, dry solid content and produce paper for further physical test. The scheme of this experiment part is as following.

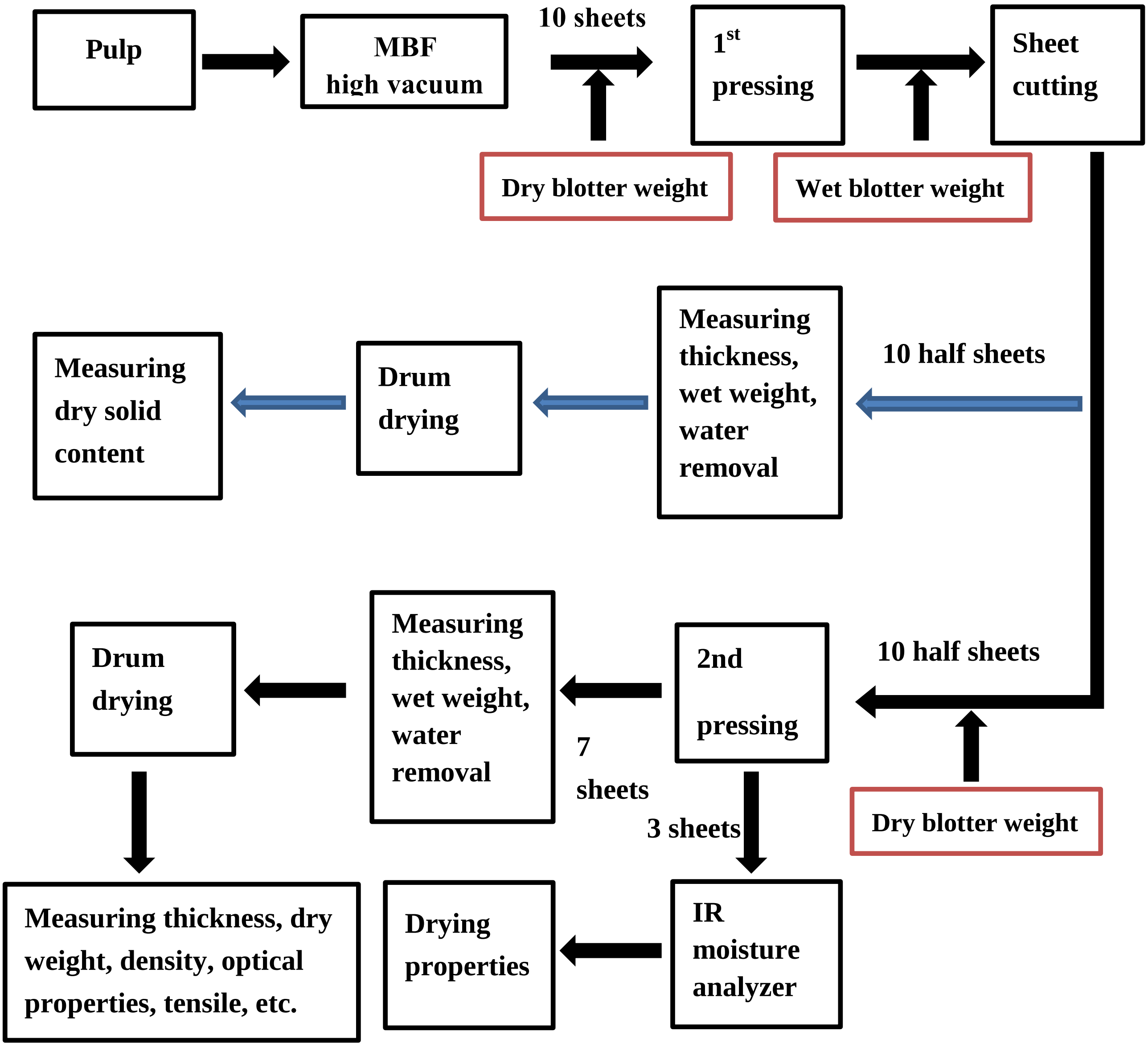

Figure 16. The scheme for evaluation the drying properties in the experiment part.

Sheet forming, storage and blotters preparation

In this part, the same methods were used to form the sheet as were used for dry solid content evaluation. However, in this part, only the high vacuum was applied. 10 sheets were formed with MBF and then each sheet was put on a plastic plate to weight the wet mass. After that each sheet with plastic plate was put into a plastic bag to prevent evaporation and storage in freezer for further testing.

Figure 17. Wet sheet with plastic plate in a plastic bag.

Blotter papers were conditioned in 90% humidity over a night to be used as a fabric for 1st and 2nd press. The weight of blotter papers was weighted before and after pressing in order to check the degree of water removal after pressing.

1st pressing

In pressing part, sheet was placed on a plastic plate and covered by a blotter paper which had been weighted before. Then, the sheet was pressed with MTS-810. The target load and pressing time of the nip was 5.5MPa for 20ms.

Blotter paper was acting as a press felt receiving the water from the sheet during the press pulse. After pressing, the wet blotter paper was weighted for the degree of water removal. Meanwhile, the sheet with plastic plate was stored back to the plastic bag for 2nd pressing.

2^{nd} pressing

Because the maximum load of MTS-810 is 100kN which equals 3.7MPa pressure for a sheetwith the size of 165mm*165mm. So before the 2^{nd} press, sheets needed to be cut half due to the increased pressure 8.8MPa for 20ms.

Then the original sheet was cut to 2 pieces. One was used to measure the wet thickness before measuring the wet weight. The other one was used to 2^{nd} pressing. When measuring the thickness, the thickness of wet sheet can creep downwards, thus, read the wet thickness after 10 seconds.

The halved sheet was pressed as 1^{st} press and water removal was measured. Right after the 2^{nd} press, the first 3 sheets were cut to small pieces with size 58mm X 58mm to fit the IR dryer. The small pieces were used to measuring the drying properties with IR dryer at 185 °C. Another 7 half sheets were used to measure the thickness and wet weight.

Drying, physical tests

The wet sheets after 1^{st} press and 2^{nd} press were dried with the drum dryer. After that the sheets are conditioned according to SCAN standard for further physical properties like thickness, density, optical properties, tensile properties, etc.

Measure methods and standard

Shopper Riegler (SR)	ISO 5267-1:1999
Water retention Value (WRV)	SCAN-C 62:00
Fine separation	SCAN-CM 66:05:2005
Fibre properties	Kajaani FS-200 Fibre analyser
Tensile strength	ISO 1924-2:2008
Optical properties	ISO 2471:2008

7. Results

7.1 Fibre Properties

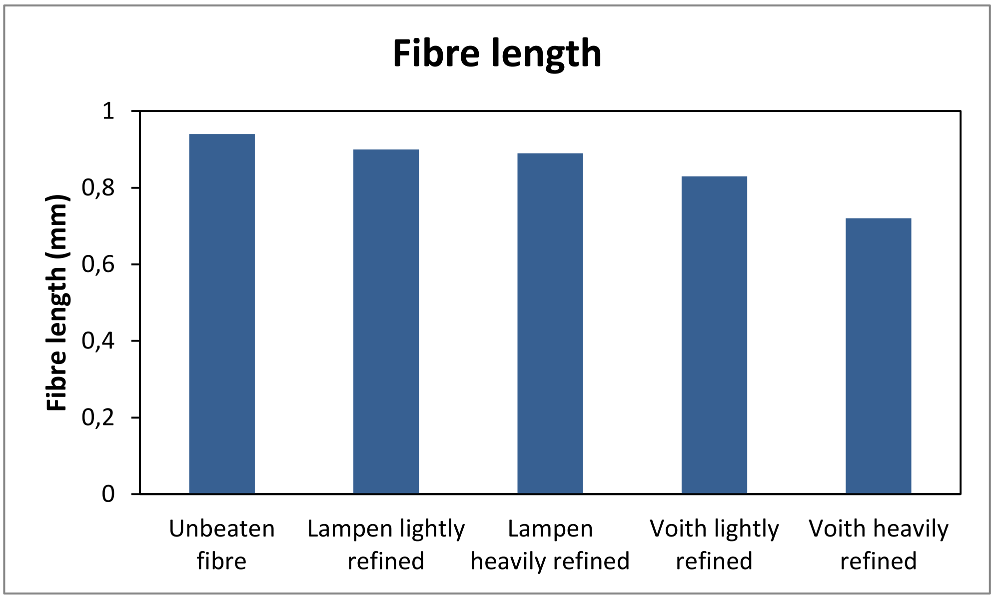

Figure 18. Fibre length after refining measured by Kajaani Fiberlab.

According to the Figure 18, comparing with the unbeaten fibre the average fibre length after Lampen mill remained almost the same, while for the fibre refined by the Voith refiner, the average fibre length decreased significantly.

The average fibre length of Lampen refined pulp remained at 0,9 mm even though increasing the revolution. The reason is that in this experiment, hardwood whose fibre length was shorter than that of softwood was used. Even though increasing the total revolution, the compressive force generated between ball and wall, was not enough to cut the fibre

With the increasing of specific refining energy, the average fibre length of Voith refined pulp decreased from 0.83 mm to 0.67 mm. It was also shown that the average fibre length of Voith refined pulp was shorter than those of Lampen mill refined pulp. In the experiment, the specific edge load was slightly lowerfor pulp with short fibre. However, the intensity was still high enough to cut the fibre.

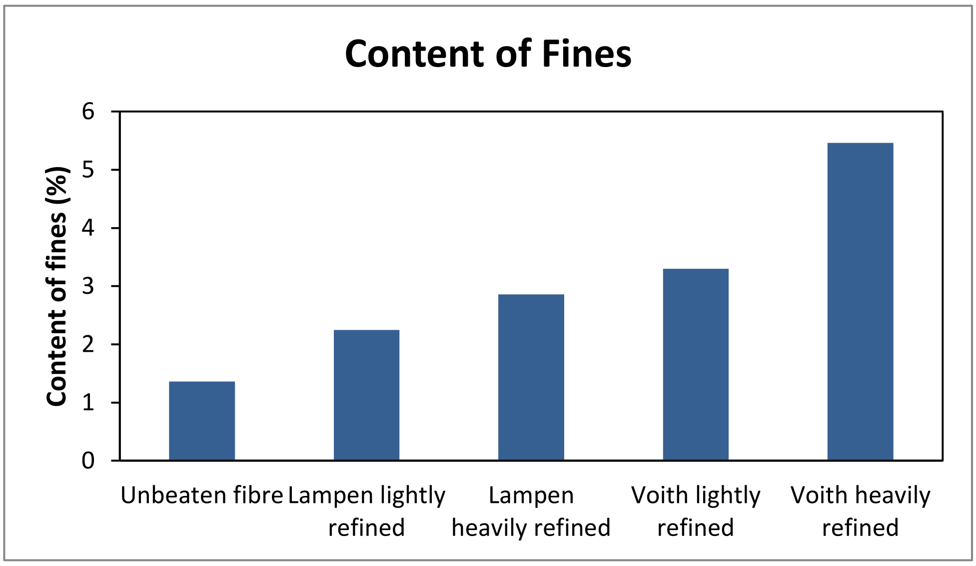

Figure 19. Contents of fine after refining measured by Kajaani Fiberlab.

According to the Figure 19, for both cases the content of fines increased after heavily refined. The content of fine with Lampen mill refiner increased from 2.3% to 2.9%, and for the pulp with Voith refiner increased significantly from 3.3% to 5.5%. It is obviously that the pulp refined by Voith refiner had more fines than that with Lampen mill refiner.

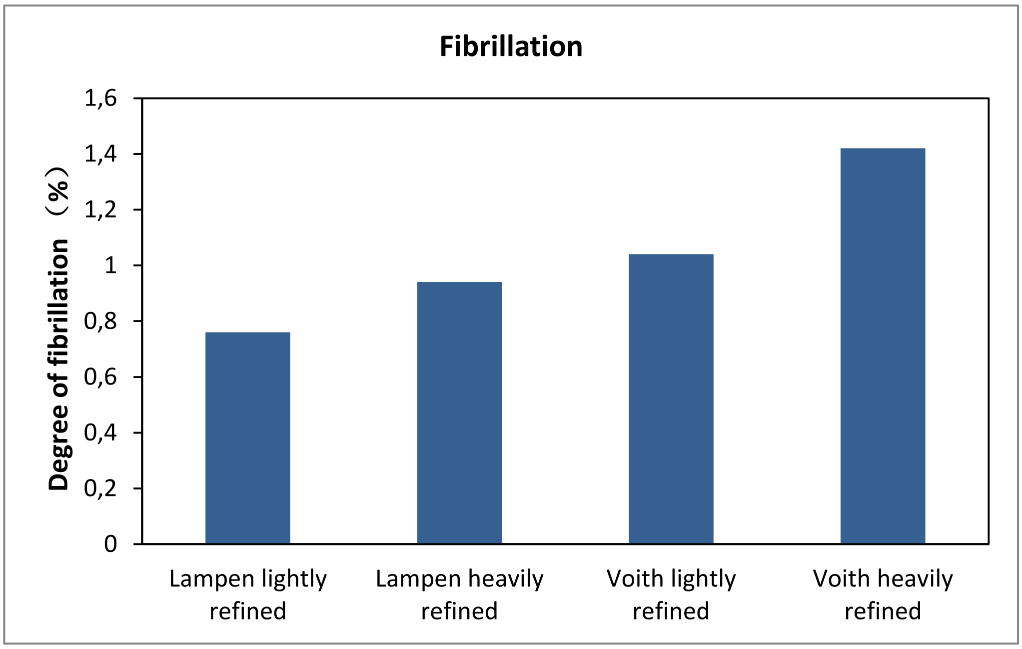

Figure 20. The degree of external fibrillation measured by Kajaani Fiberlab.

As it shown in Figure 20, the degree of fibrillation increased with the increasing refining energy. More heavily refined fibres, the higher degree of external fibrillation. Like the content of fines in Figure 19, the degree of external fibrillation with Voith LR-40 refiner increased significantly from 1% to 1.5%, while the pulp with Lampen mill refiner rise from 0.8% to 1%.

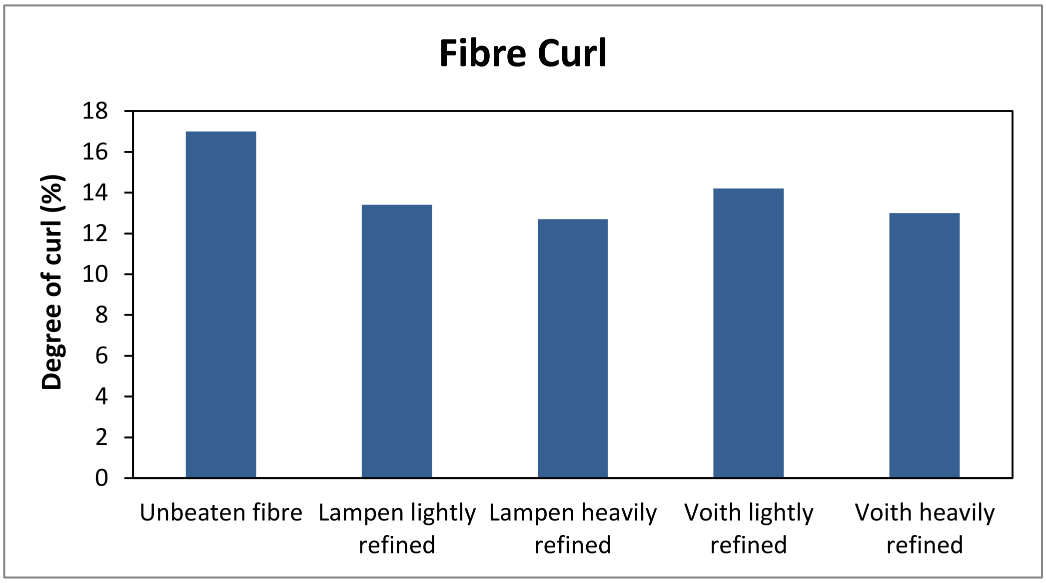

Figure 21. The degree of fibre curl measured by Kajaani Fiberlab.

It is shown that heavily low consistency refining can reduce the degree of fibre curl in both cases. As the fibre length of hardwood is short, so with the increasing of refining energy, the degree of fibre curl cannot be reduced largely. However, fibres after Lampen mill refined were straighter than that of Voith refined fibres.

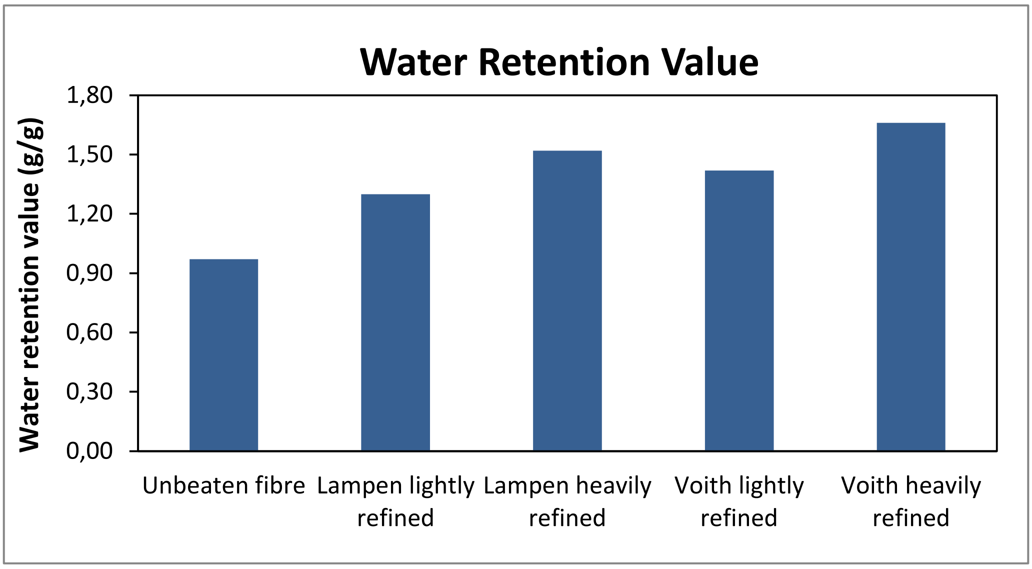

Figure 22. The water retention value.

According to the Figure 22, heavily refined increased the water retention value. The value of Lampen mill refined pulp rose from 1.3 to 1,5 and for Voith refined pulp it increased from 1.4 to 1.6. The water retention value indicated the content of fines, fibre swelling degree and external fibrillation can affect the water retention value.

7.2 Forming part

As mentioned in the experiment part, the samples were formed with Moving Belt Former (MBF). The vacuum level was measured in the suction box when the vacuum applied on the wet web. Here, the typical low and high vacuum curves are shown in Figure 23. The value of high vacuum level can reaches about 40, while the low vacuum level is around 14. There are two stages of high vacuum levels, the first stage is low vacuum level from 80000ms to 100000ms which is the same as the only low vacuum applied, and the second stage is high vacuum level from 100000ms to 120000ms.

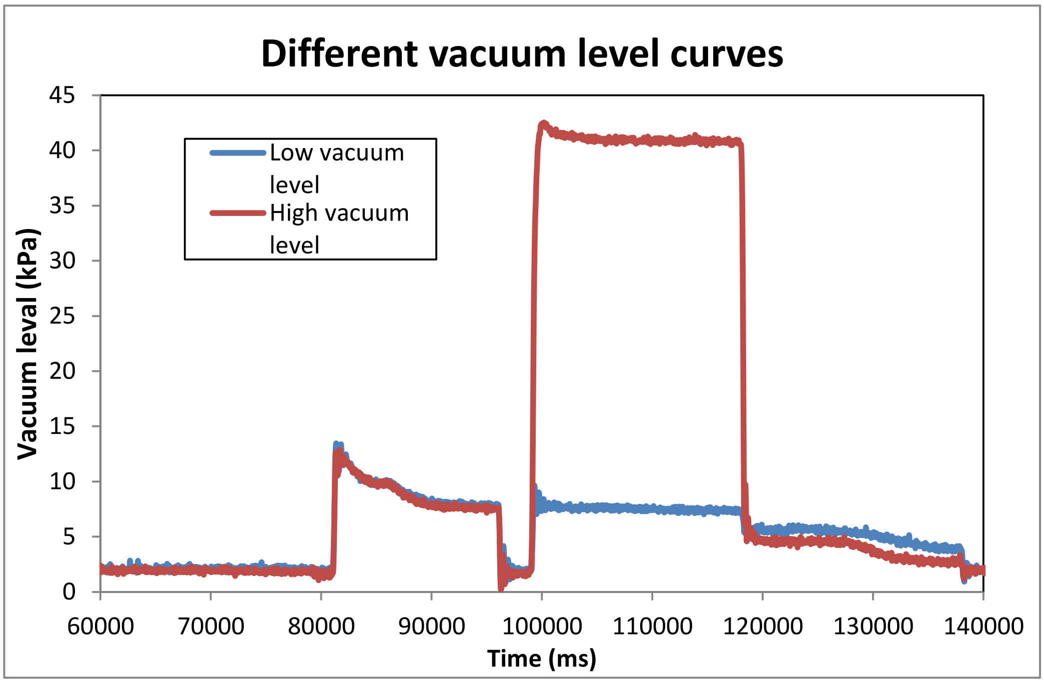

Figure 23. The typical low and high vacuum curves in MBF.

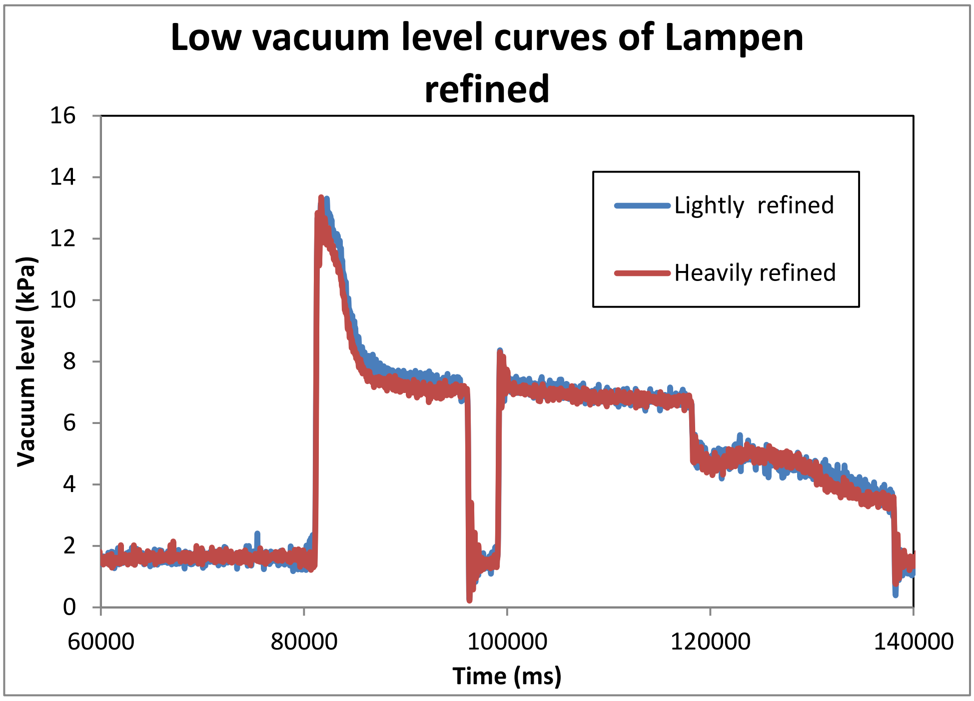

Figure 24. Lightly vacuum level curves of Lampen mill refined with MBF forming.

When low vacuum was applied, the vacuum curves of lightly and heavily refined Lampen mill pulp were overlapped.

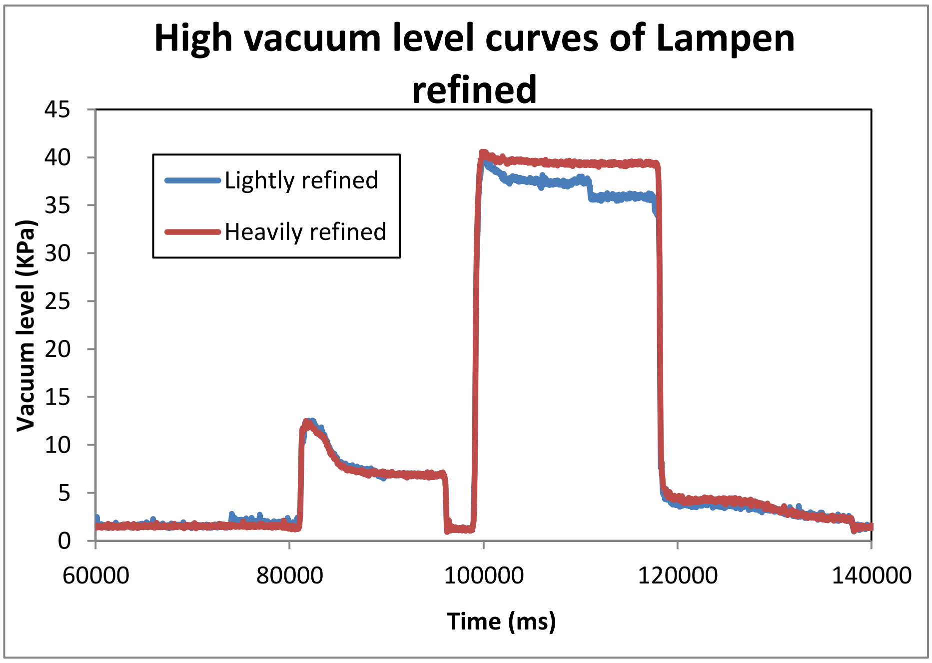

Figure 25. High vacuum level curves of Lampen mill refined with MBF forming.

As it is expected, unlike low vacuum level, when high vacuum applied, heavily refined pulp responded higher than the lightly refined sample. The reason is that heavily refined pulp had more fines and higher fibre swelling than the lightly refined pulp. Also, the heavily refined pulp had higher degree of fibrillation. The higher fines content, higher fibre swelling, more fibrillation, the denser of wet fibre web, resulted in higher resistance against the air flow.

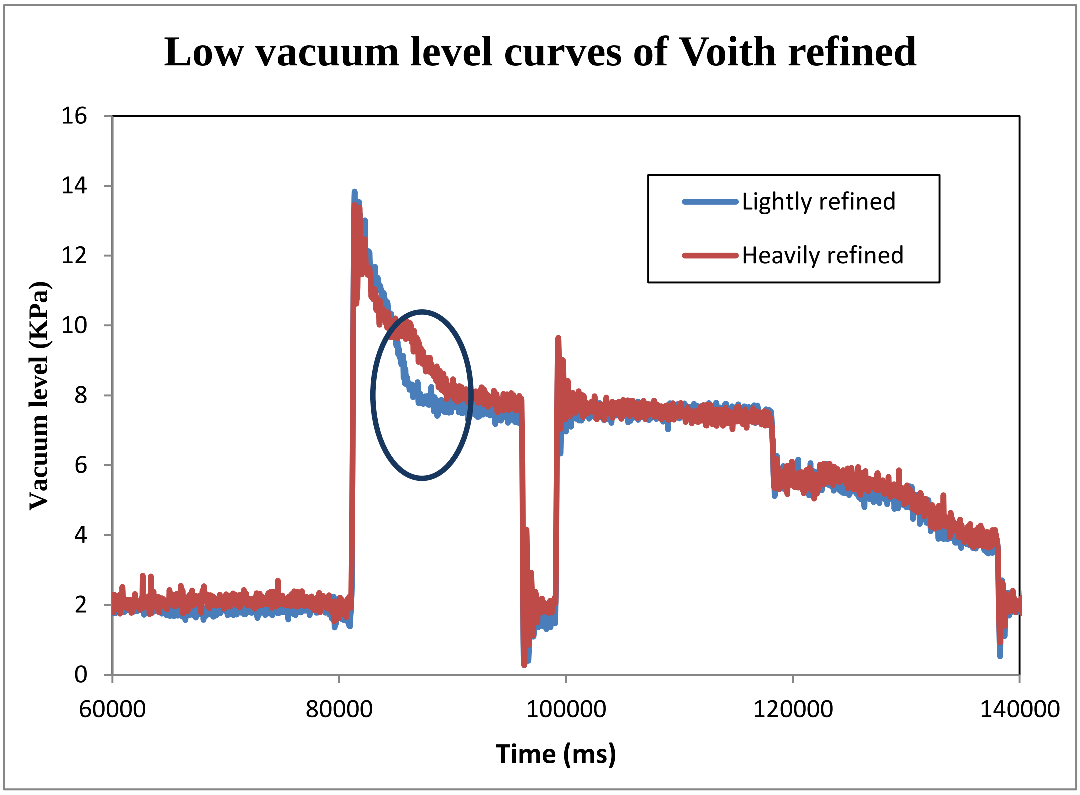

Figure 26. Lightly vacuum level curves of Voith LR-40 refined with MBF forming

Like Figure 24, the same phenomenon was observed when low vacuum was applied on the Voith refined fibre web as shown in Figure 26. However, in the circle area, the difference can be seen that heavily refined pulp responded more than the lightly refined pulp against air flow. This is because of Voith refined pulp had more fines, higher fibrillation and higher swelling than Lampen refined pulp. It was indicated that the amount of fine mainly affected the responded even though there was low vacuum applied.

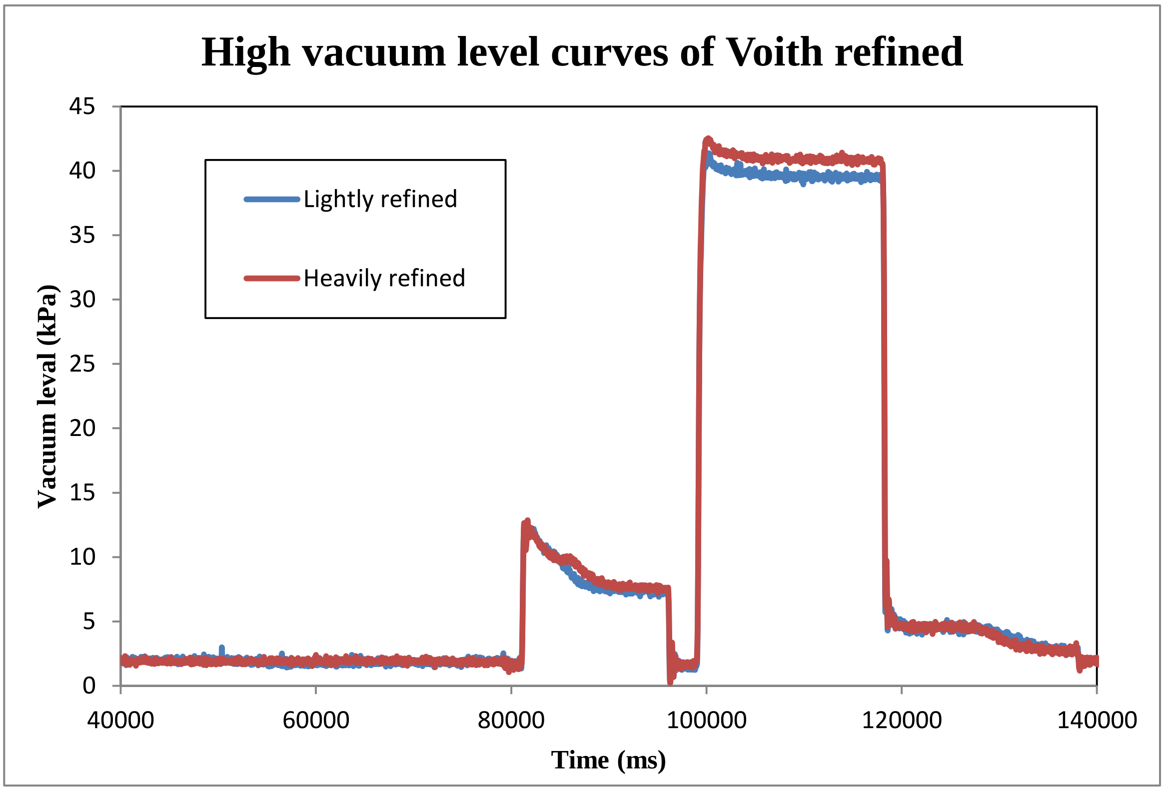

Figure 27. High vacuum level curves of Lampen refined with MBF forming.

It is obvious that heavily refined pulp responded more than that of lightly refined pulp in both low vacuum and high vacuum area as the same shown in Figure 25.

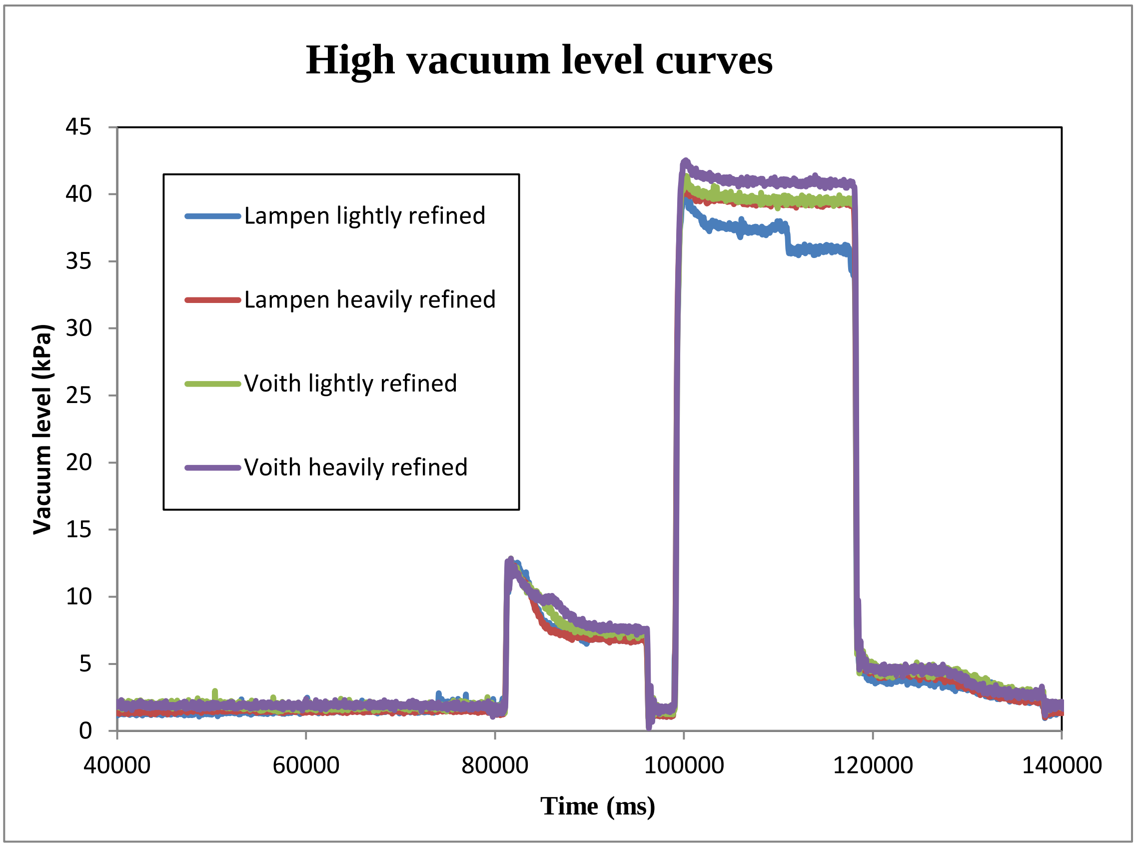

Figure 28. High vacuum level curves of both Lampen and Voith refined pulp.

It is clearly seen that how the amount of fines influence the wet fibre web responded to the air flow. The amount of fine for Lampen refined were 2.3%, 2.9%, 3.3% and 3.3% and 5.5% in Voith refined cases. For Voith refined pulp the maximum vacuum were both above 40 kPa, while for Lampen refined pulp the number were below 40 kPa.

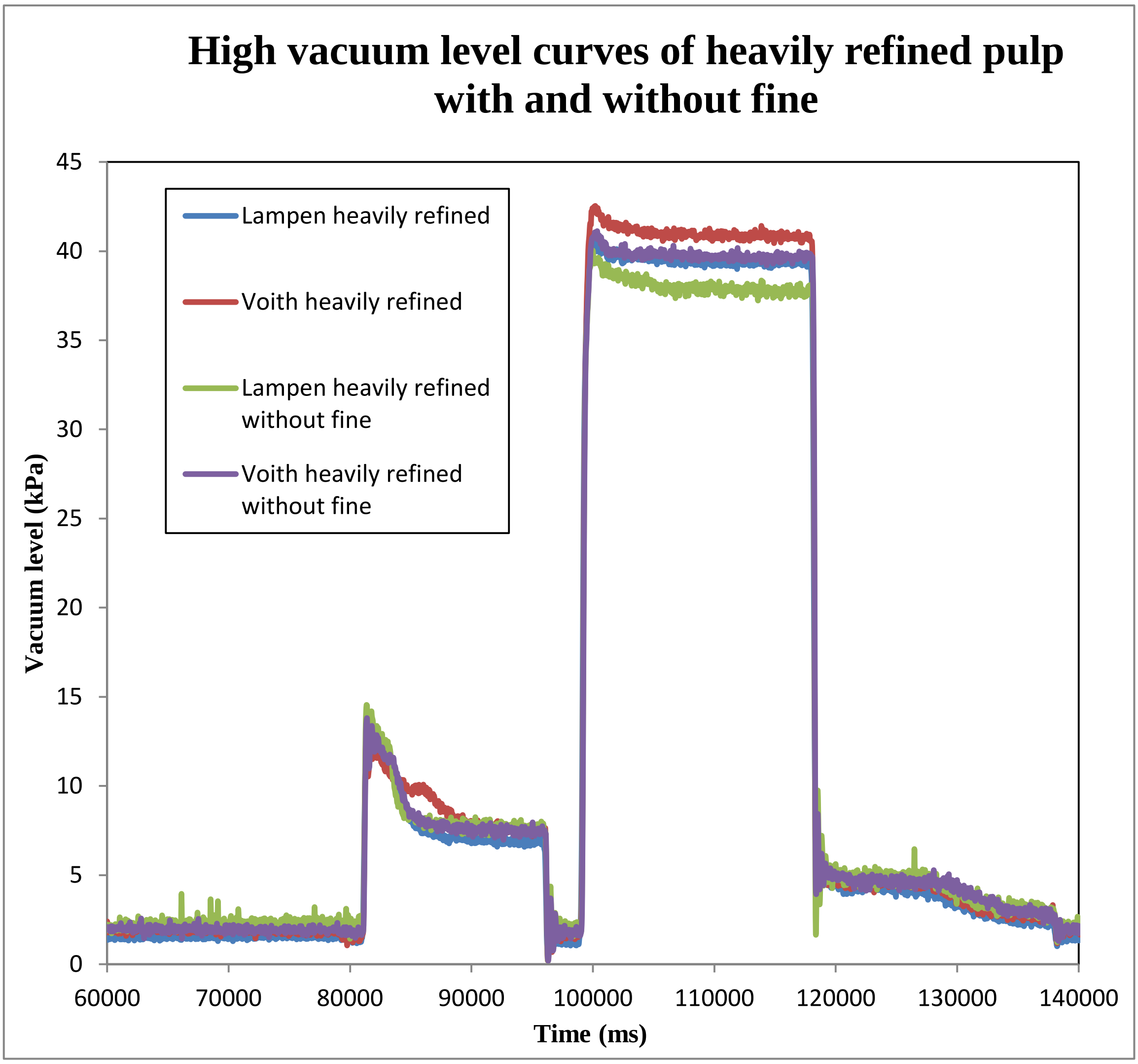

Figure 29. High vacuum level curves of heavily refined pulp with and without fine.

When the pulp were got rid of fine as much as possible, it is obviously seen that the maximum vacuum level were below their original pulp.

However, the curve of Lampen refined pulp and heavily refined pulp without fines were overlapped, which means the difference content of fines are not the only effect influencing the dewatering property. It is supposed that external fibrillation and fibre swelling degree also affects dewatering.

As it is mentioned in experimental devices part, the pulp was mixed first in the mixing and forming chamber of the MBF and then the plastic sheet was pulled out. Once, the pulp goes into the forming chamber, the surface level is the highest point. The following surface's levels development was detected. The heavily refined pulp had higher fines and water retention value which result in the delay of drainage.

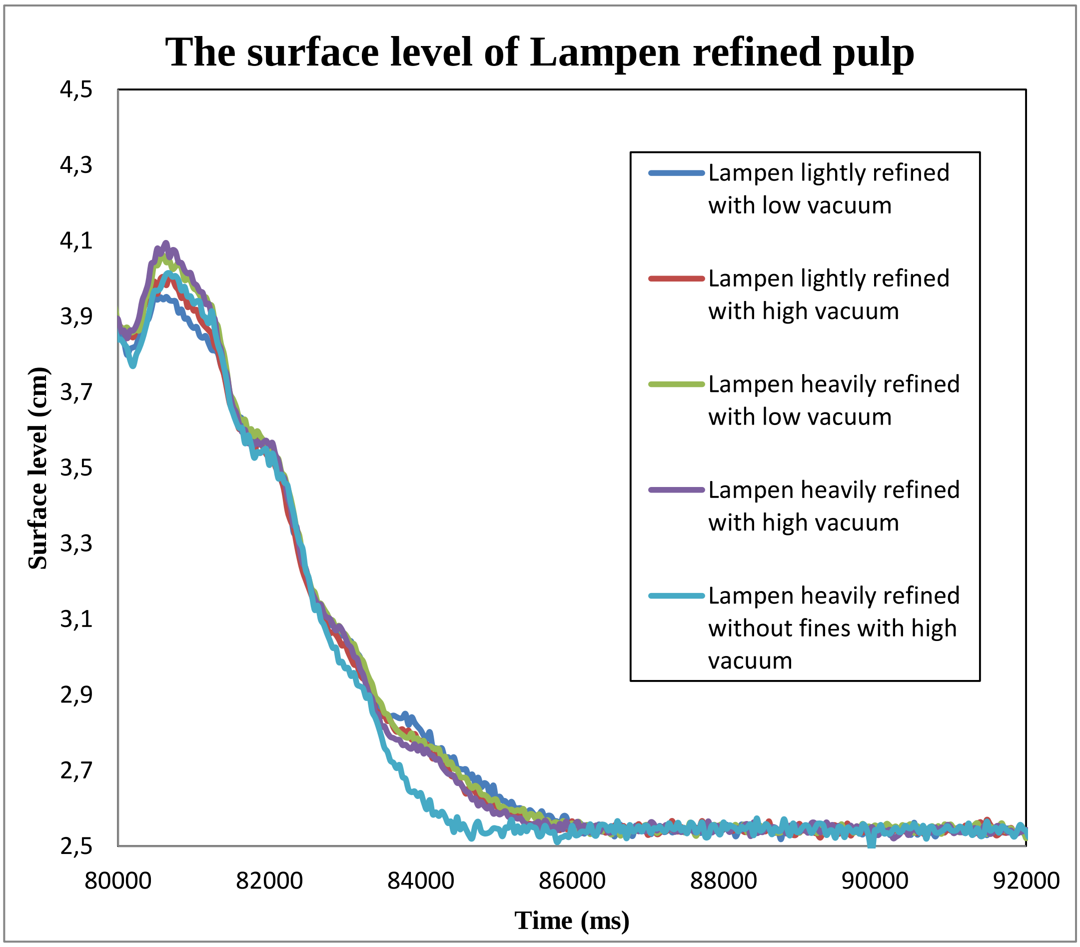

Figure 30. The surface level of Lampen refined pulp.

According to Figure 30, the drainage time of Lampen refined pulp were the same at 5000ms, which indicate that the drainage time in Lampen refined pulp cases were not depending on the fines content and vacuum level. Pulp without fines had a lower drainage time at 4000ms.

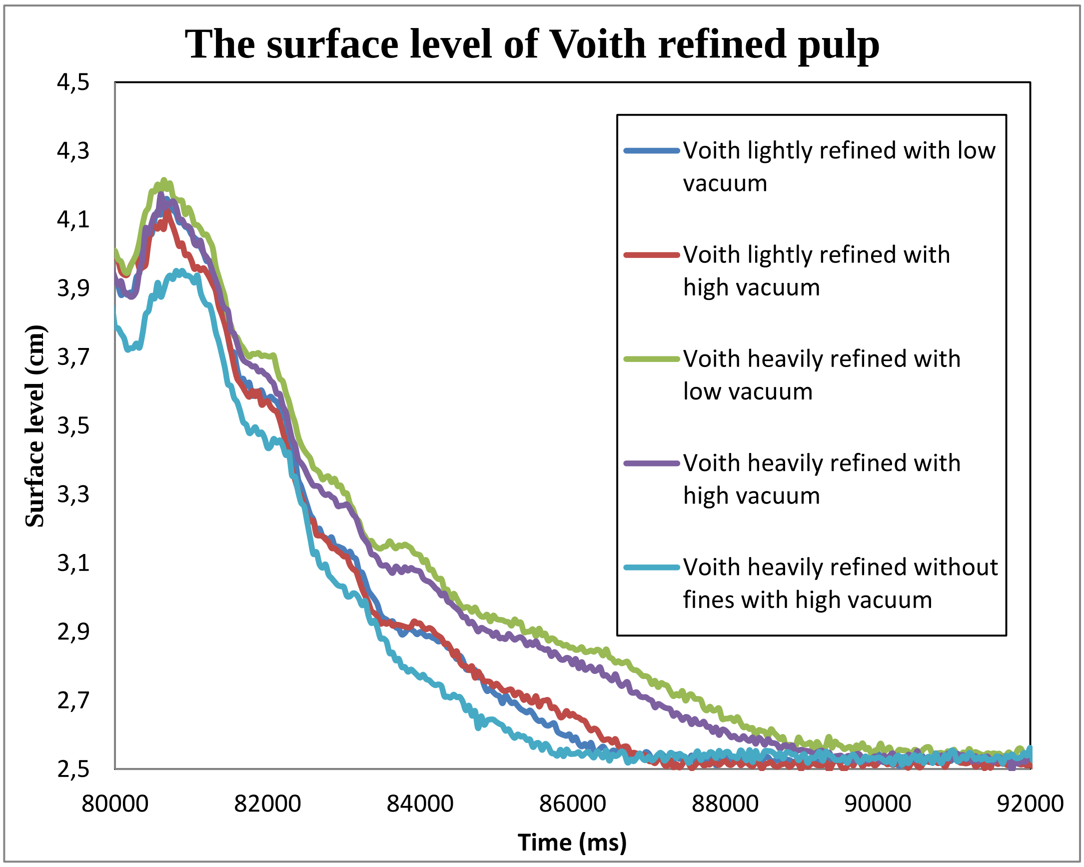

Figure 31. The surface level of Voith refined pulp.

It can be clearly seen that there were three drainage time: Voith heavily refined, Voith lightly refined and Voith heavily refined without fine. The heavily refined pulp was the longest while the pulp without fine was the shortest. The drainage times were 9000ms, 6500ms and 5000ms respevtively. Comparing with Lampen refined pulp, the same phenomenon was observed that the drainage time does not depending on the vacuum level. The higher the fines content, the longer drainage time.

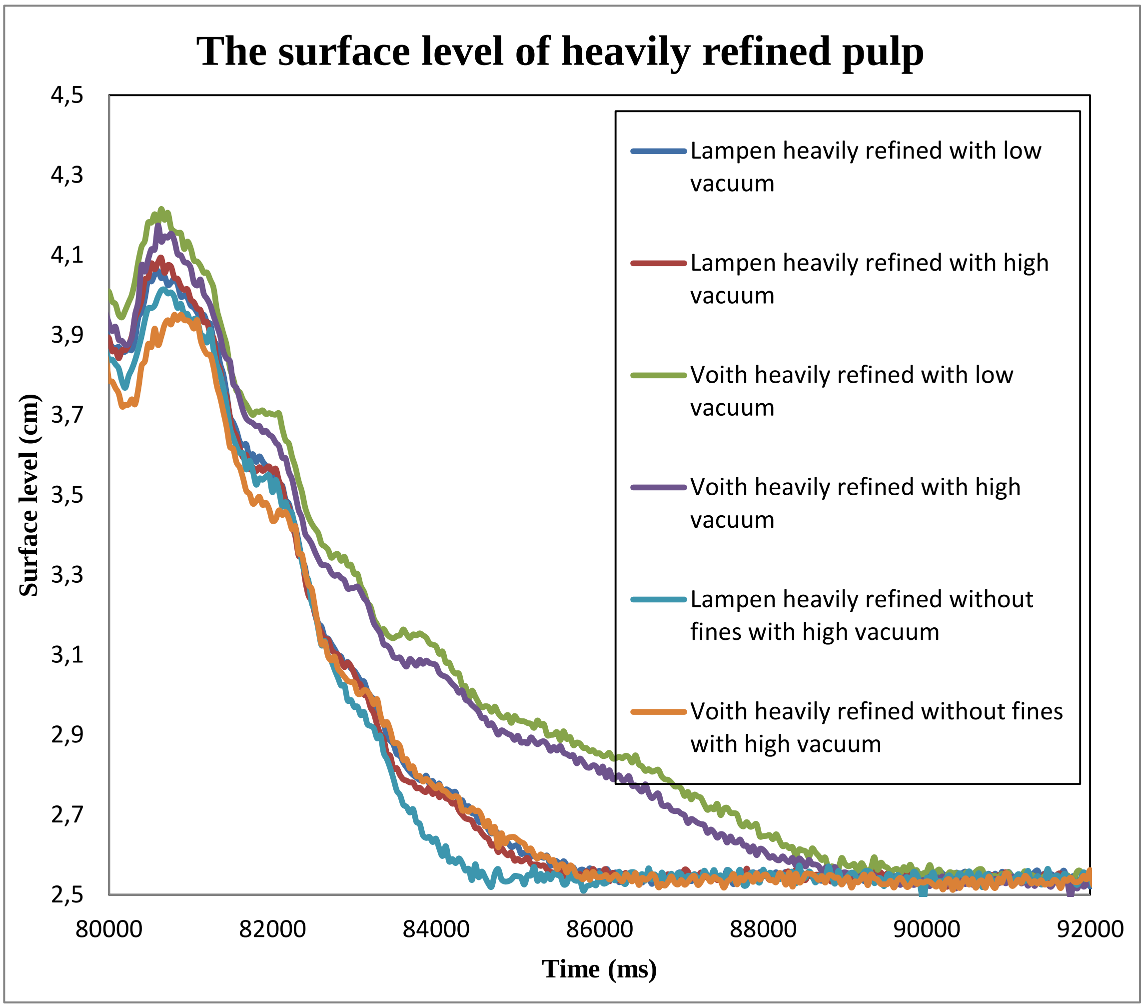

Figure 32. The surface level of heavily refined pulp.

Comparing Lampen refined pulp and Voith refined pulp, we can see that the drainage time of Voith refined pulp are much longer than that of Lampen refined pulp, which is mainly due to Voith refined pulp containing more fines. However Voith refined pulp without fines possess the same with Lampen refined pulp, which indicate that there are some other reasons influencing the time such as fibre swelling and fibrillation.

7.3 Drying solid content

After forming with the MBF, the sheets were pressed by MTS-press. The MTS can generate short pulse like in a mill scale roll press nip. There were two stages of press with different setting conditions. The dry solid content was measured after forming, 1st pressing and 2nd pressing.

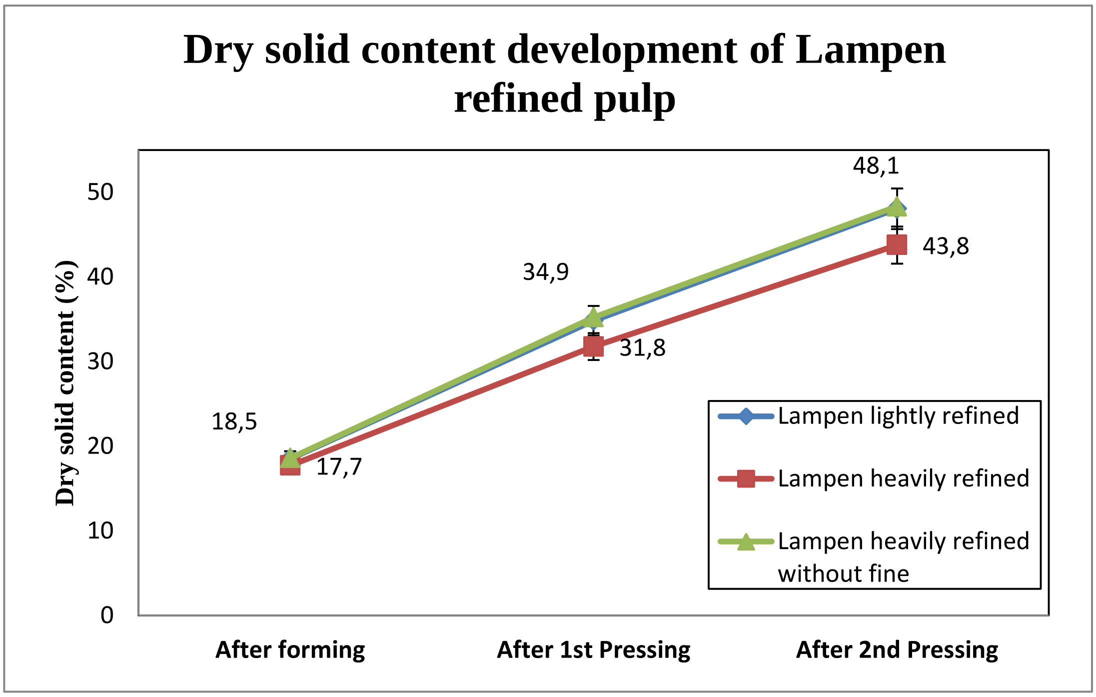

Figure 33. Dry solid content of Lampen mill refined pulp in each sub-process.

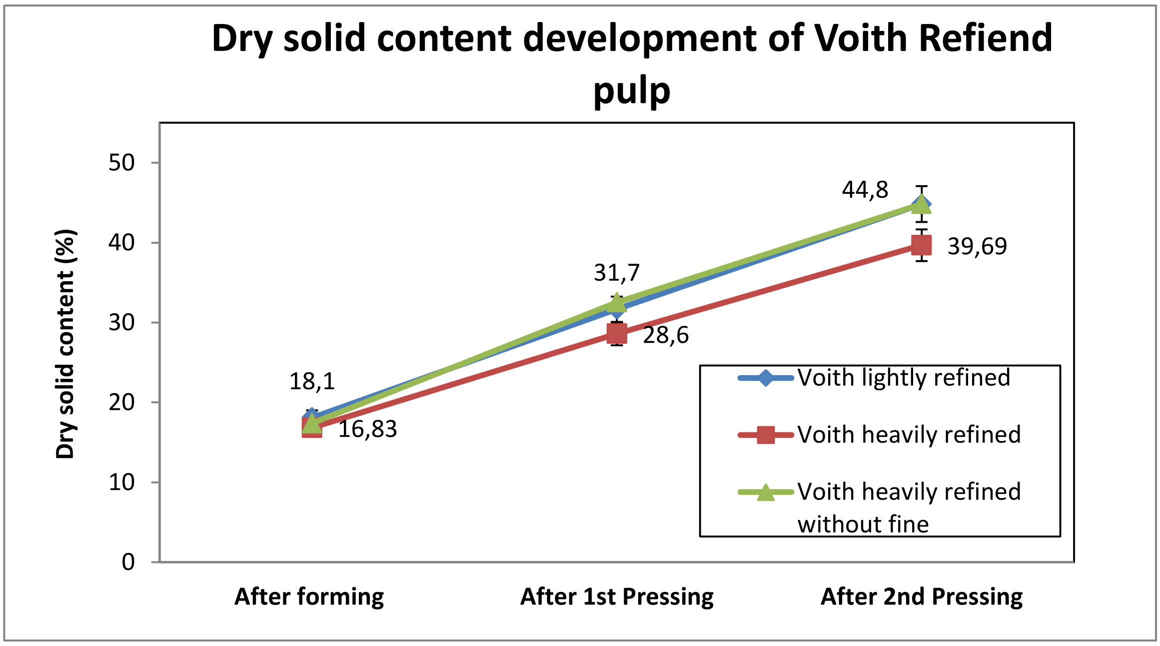

Figure 34. Dry solid content of Voith refined pulp in each sub-process.

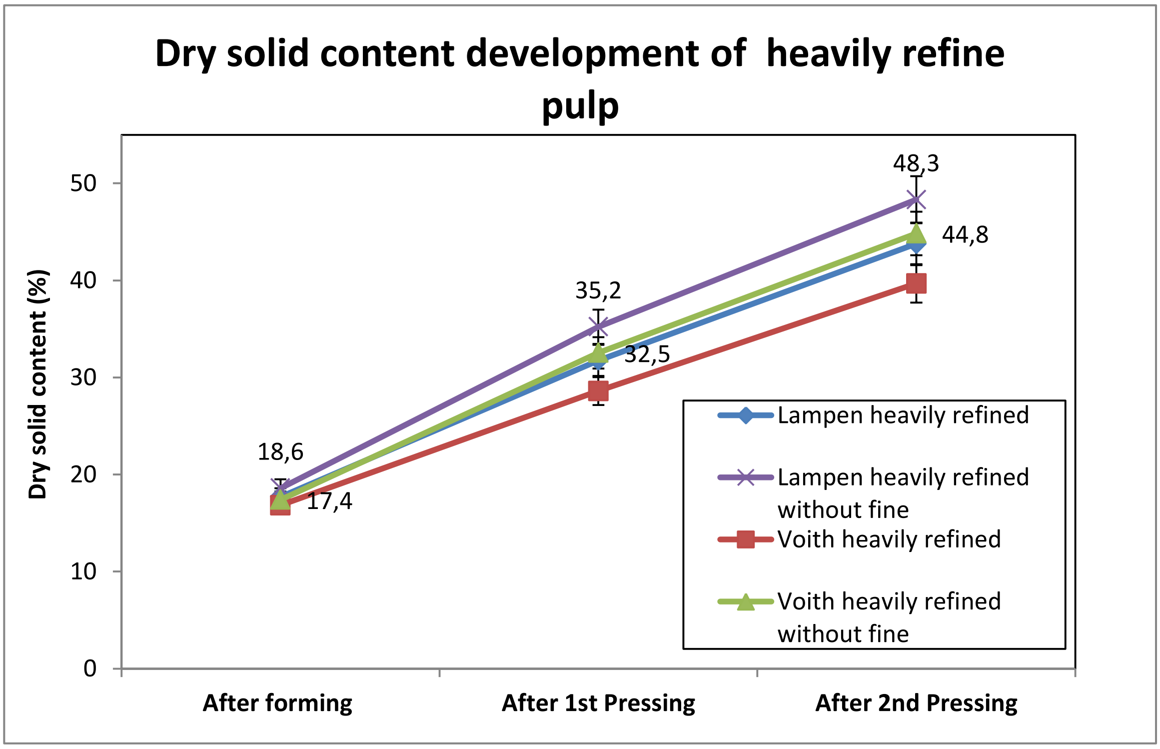

Figure 35. The different dry solid contents of Lampen and Voith heavily refined.

Figure 33 and Figure 34 shows the dry solid content development in each sub-process and the value are the lightly refined and heavily refined samples. Figure 35 shows the different results of heavily refined samples and heavily refined without fines sample and the value are the refined samples without fines. It is clearly seen that there is a linear increasing tendency in all cases.

The dry solid content of heavily refined samples was lower than that of lightly refined samples. Figure 35 shows the reason that samples with higher fines content had lower dry solid content. Therefore, heavily refined samples had more fines content and fibrillation than that of lightly refined samples which result in higher water retention value. Due to the limitation of vacuum dewatering, more water retains inside fibres and between fibres in heavily refined samples. Flow is also limited due to the difference in the permeability of the sheets. Figure 40 shows that heavily refined samples had lower permeability.

However, the curves of lightly refined sample and heavily refined without fines samples were overlapped in both Lampen refined and Voith refined cases. Heavily refined without fines samples had lower fines content, but had more fibre swelling and fibrillation than those of lightly refined samples.

The interesting thing was that the dry solid content differences between lightly and heavily refined pulps become bigger after each step. After forming, the dry solid content of lightly refined samples was only 1% higher than that of heavily refined. After 1st press, the gap reached to 3% and finally in 2nd press the number was 5%. The reason might be that water retained in the fibres creates hydraulic resistance which can against the press load. There was no press load in forming part, thus the dry solid content difference was smallest.

7.4 Drying properties with IR dryer

After 2nd pressing, part of sheets were cut to a certain size and then dried by IR dryer where the drying rate can be obtained. The Figure 36 shows that the drying rate of Lampen lightly refined sample was the fastest among there four sample, while Voith heavily refined sample was the slowest. Permeability of the samples is the most probable descriptor for drying rates observed. The results of Gurley permeability in Figure 40 related to the drying rate. The Lampen lightly refined sample had the highest value while Voith heavily refined sample had the lowest.

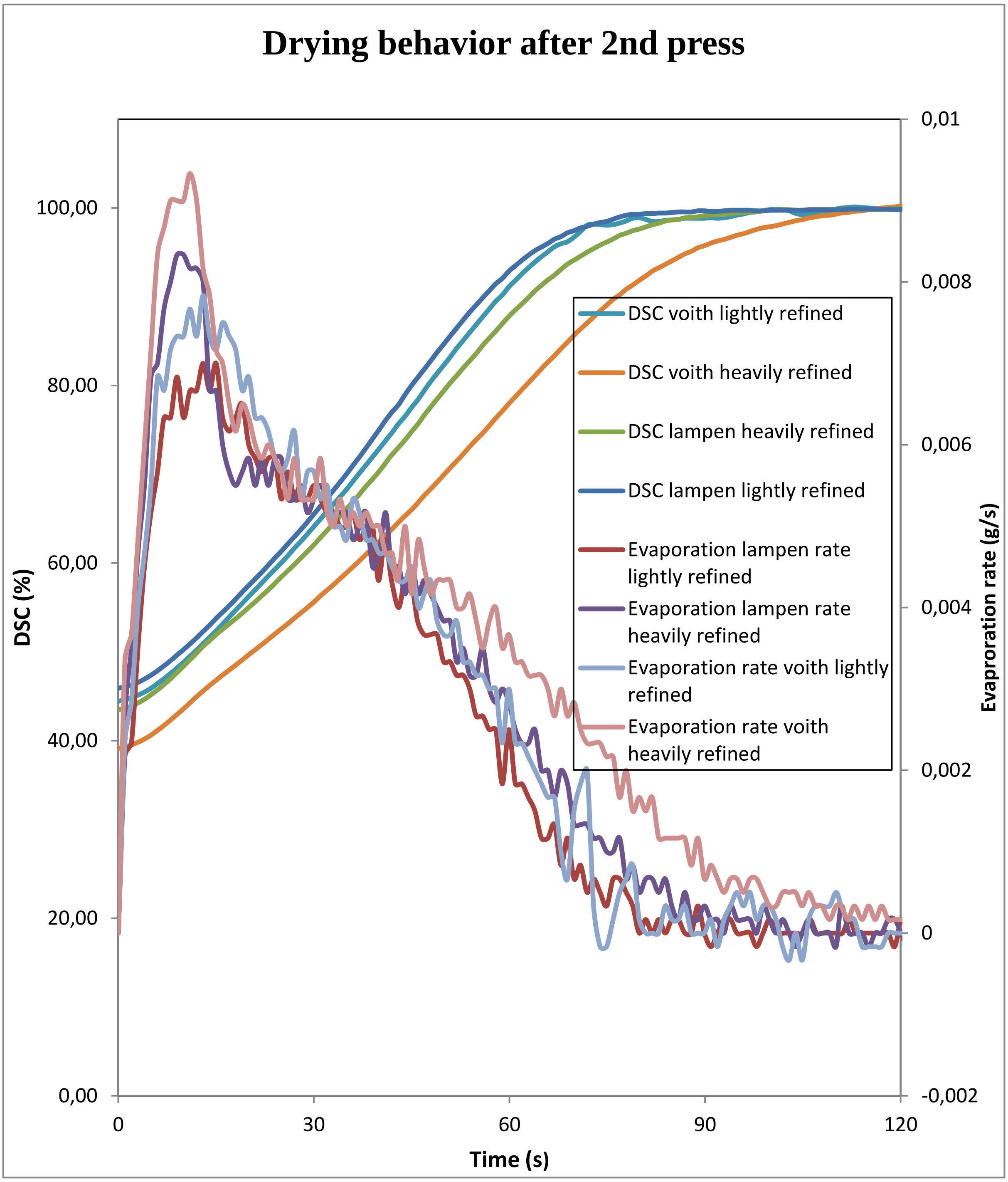

Figure 36. Drying behaviour after the 2nd press.

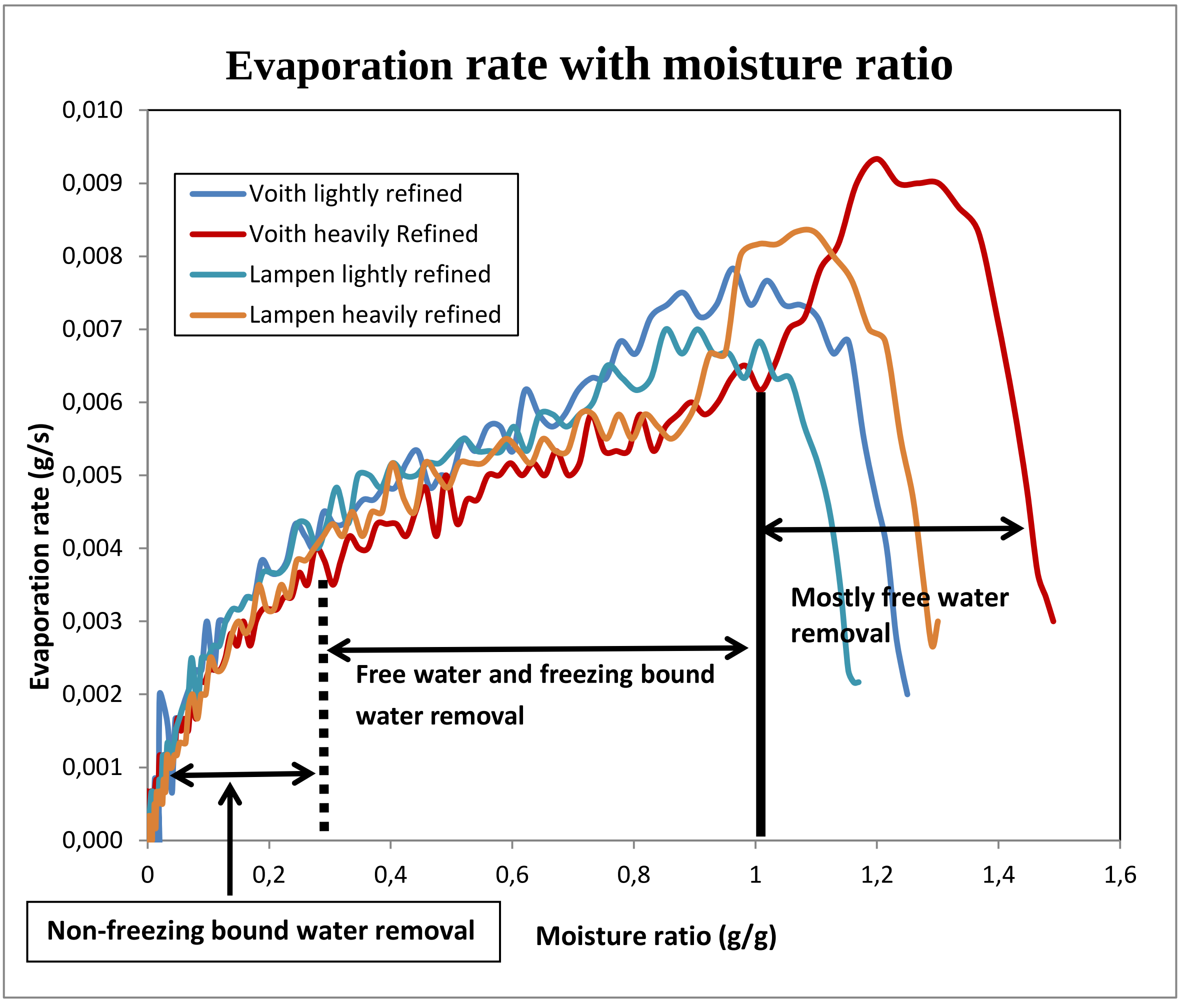

Figure 37. Evaporation rate with the moisture ratio.

According to Figure 37, lightly refined sample had higher evaporation rate than heavily refined sample in both cases. This again explained due to the higher permeability. However, the lightly refined Voith and Lampen sample had the same evaporation rate and the same phenomenon was observed in heavily refined samples. In general, the higher density and permeability, the faster drying rate. Higher density improves internal heat conduction and transfer in the sheet, while lower permeability impairs water vapour transfer through the porous web structure. Therefore, the net effect in the drying rate can be eliminated. Lightly Lampen refined pulp had higher permeability and lower density, while lightly Voith refined sample had lower permeability and higher density. The same phenomenon was in heavily cases. These two factors might be neutralized each other to have the same evaporation rate.

The water inside the cell wall were consisted of bulk water or free water and bound water which is composed of freezing bound water and non-freezing bound water [15].The drying process can be divided into three parts according to Weise's research [16]. The first part, where is the heating part the temperature starts from 0 to 180℃, only the free water was removed as much as possible. The second part, where the temperature remained at 180℃, the freezing water which located in small pores starts to be removed. The last part, the non-freezing bound water starts to be removed. The hydrophilic groups may absorb water forming non-freezing bound water [16].

7.5 Physical and optical properties

7.5.1 Physical properties

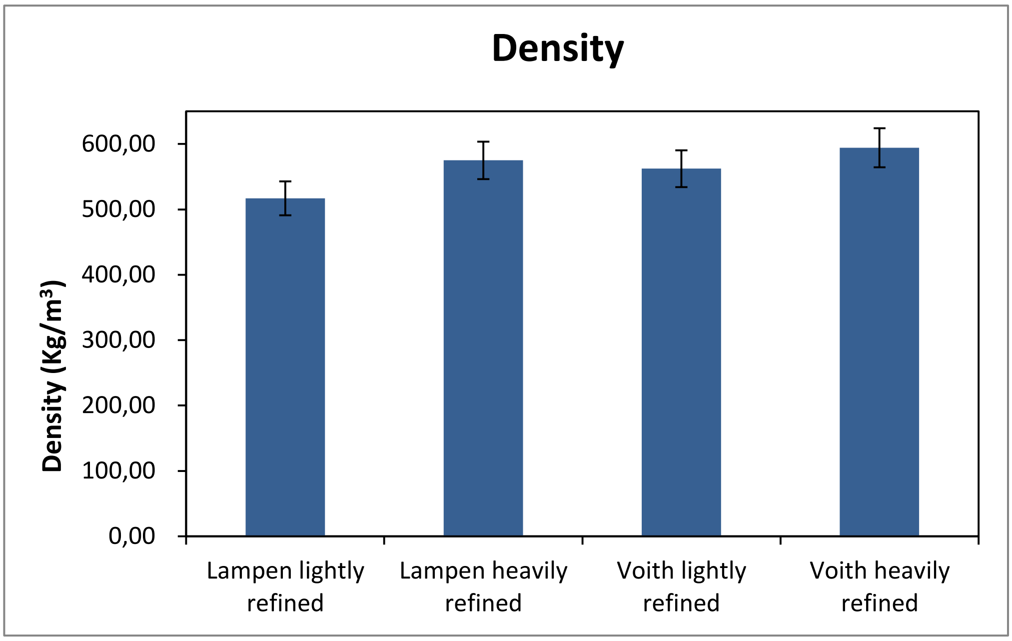

Figure 38. Density of Voith refined and lampem mill refined samples.

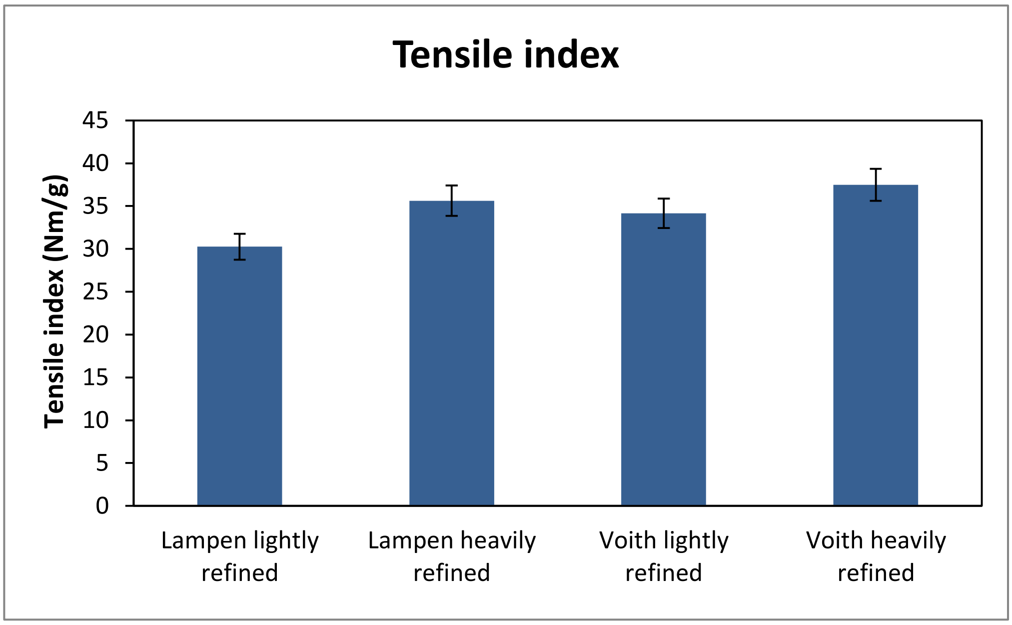

Figure 39. Tensile index of Voith refined and lampem mill refined samples.

Figure 38 and Figure 39 show the density and tensile index properties of after 2nd pressed sheets. The density of heavily refined pulp was higher than that of lightly refined pulp in both Voith and Lampen refined methods. The density is correlation of the vacuum level properties when forming sheets. The denser web, responded higher against air flow which result in the high vacuum level.

The same phenomenon was observed in tensile index that heavily refined pulp samples had higher tensile index than that of lightly refined samples in both Voith and Lampen cases. The degree of fibrillation determine the tensile index that the higher internal fibrillation, the higher tensile index. The fibre length was reduced after heavily refined, however the tensile index increased, thus the fibre length does not influence the tensile index.

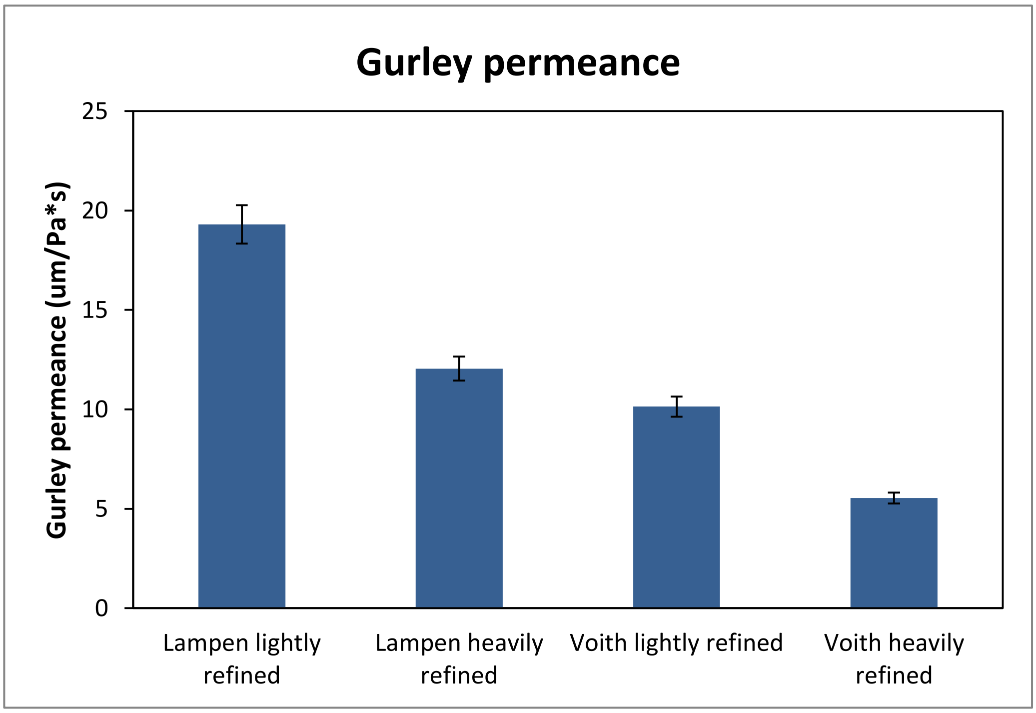

Figure 40. Gurley permeance of Voith refined and lampem mill refined samples.

The Gurley permeance represented the ability of drying rate which illustrated in Figure 36 and Figure 37. Heavily refined samples had lower Gurley permeance which means the air pass through the sheet and water evaporate out of sheets both need more time. Voith refined samples had lower Gurley permeance than that of Lampen refined samples. The reason is that increased density causes lower permeance.

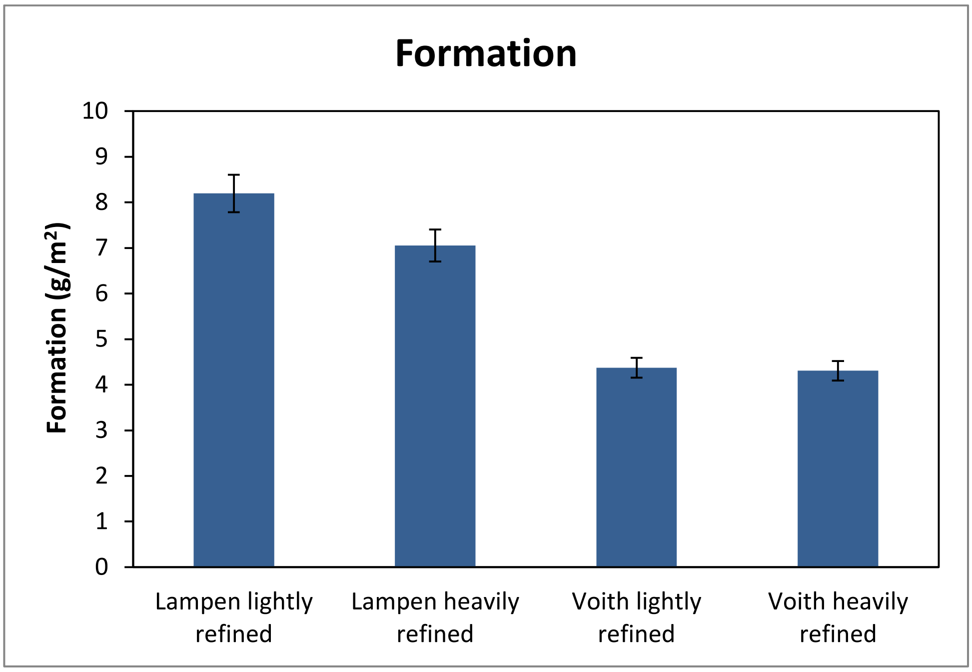

Figure 41. Formation of Voith refined and lampem mill refined samples.

MBF sheets possess lower quality of formation than another sheets forming with other method. There are two reasons that the stirrer inducing high rotation and the moving belt enforce fibres toward the running direction of belt. Due to these two reasons, the mass distribution is not as evenness as other forming methods.

Lampen refined samples had much poorer formation quality than that of Voith refined sample. For Lampen refined samples, the formation was above 7 g/m^2 while for Voith refined samples the value was around 4 g/m^2. Heavily refined samples had better formation quality in Lampen refined case while there was no large difference in Voith refined case. Probably explanation for better formation of Voith refined samples is the lower fibre length than that of Lampen refined samples.

7.5.2 Optical properties

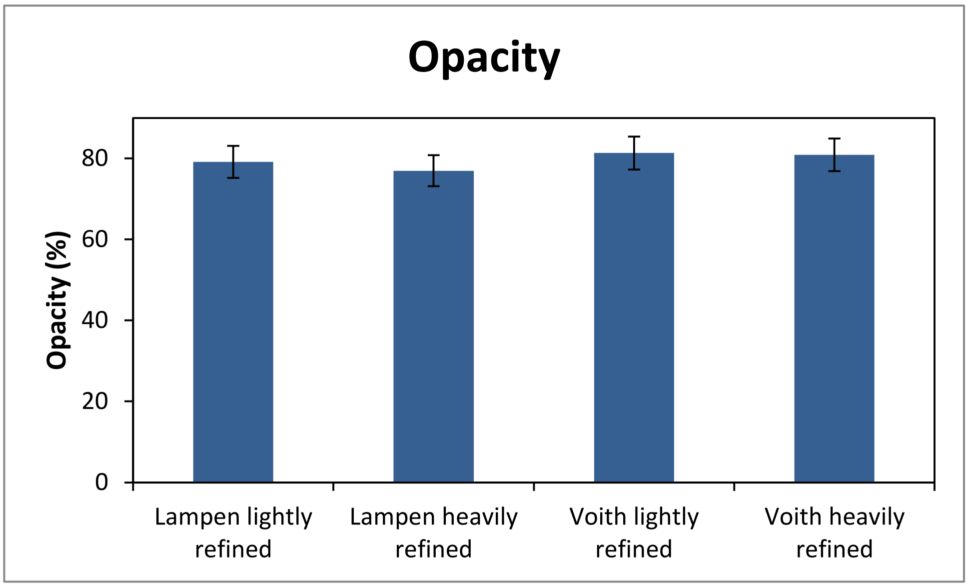

Figure 42. Opacity of Voith refined and lampem mill refined samples.

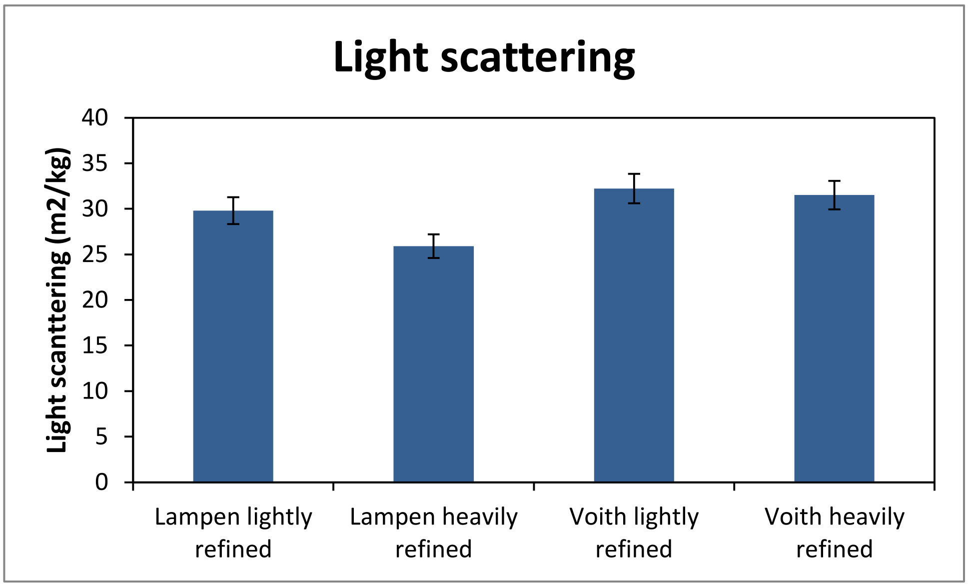

Figure 43. Light scattering of Voith refined and lampem mill refined samples.

Figure 42 and Figure 43 shows the optical properties. Both opacity and light scattering were decreased after heavy refining. The reason is that heavily refined samples have more fine and fibrillation results in denser structure of network, thus, denser web reduces the optical properties.

8. Conclusion

The purpose of this thesis was to evaluate the effects to dewatering properties in each sub-process including forming, pressing and drying. Thus, this thesis more focused on the properties variation including the fibrillation, fine contents etc. As it shown, the experiments were carried out close to the mill scale condition as much as possible due to using some non-conventional equipment.

In refining part, Lampen mill refiner and Voith LR-40 refiner was used to generate different types of furnish by control the refining energy level. Especially, the Voith LR-40 refining station is a laboratory refiner which is close to mill scale refiner by control the refining intensity and energy level. By using different energy level, 4 different furnishes were produced and fibres properties were changed compared with original fibres. However, the heavily refined fibres changed more than lightly refined. The heavily refined fibres were shorter, had more fibrillation, fines and were straighter than that of lightly refined. The same phenomenon was observed when compare Voith refind samples and Lampen refined samples that the former one is higher.

In forming part, sheets were formed by using moving belt former (MBF) where can generate high shear force for mixing and high vacuum for dewatering. At the same time the vacuum curves and surface level curves can be characterized by MBF. 4 different type furnishes were tested with low and high vacuum. When low vacuum applied the curves were overlapped, however, the situation were changed when high vacuum level applied. The heavily refined pulps or high fine content furnishes have higher vacuum curves and longer drainage time because the fibrillated and more fines content result in the denser web and less permeable. However, when Voith heavily refined samples get rid out of fines, the vacuum curve was still higher than that of Lampen refined pulp. The reason is that fibrillation, fibre swelling and fines altogether induce the higher curve.

Wet sheets were pressed twice with different pressure after forming. The MTS-press can generate pressure pulses similar to those found in a paper machine press part. Also, this device can generate high pressure in a very short time.

The dry solid content was evaluated in three sections: after forming, after 1st press and after

2^{nd} press. Heavily refined pulps have lower dry solid content than that of lightly refined and Voith refined pulps have lower dry solid content than that of Lampen refined pulps. The dry solid content developing becomes larger after each sub-process in all 4 type pulps. The gap after forming was small, however it becomes larger after 2^{nd} press. Heavily refined pulps have more fibrillation, swelling and fines contents which result in higher water retention value, thus, more water retains inside fibres and between fibres in heavily refined furnishes. This part of water can generate hydraulic resistance which can work against the press load.

After pressing, wet sheet was dried by IR-dryer to evaluate the evaporation rate. Due to the different permeability of samples, different drying rates curves were obtained. The heavily refined pulps or more fines content had lower speed in drying. The drying process can be divided into three parts: firstly free water was removed, secondly freezing water was removed and lastly non-freezing bound water starts to be removed.

The physical properties and optical properties were measured. The heavily refined furnishes have higher density. Even though heavily refined wet sheets have higher thickness than lightly refined wet sheet after wet pressing, sheets after drying the thickness become lower. The high density results in the high tensile strength index and low Gurley permeance. Heavily refined pulps have denser web, thus, it reduces optical properties.

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Appendices

Fibre properties developemnt

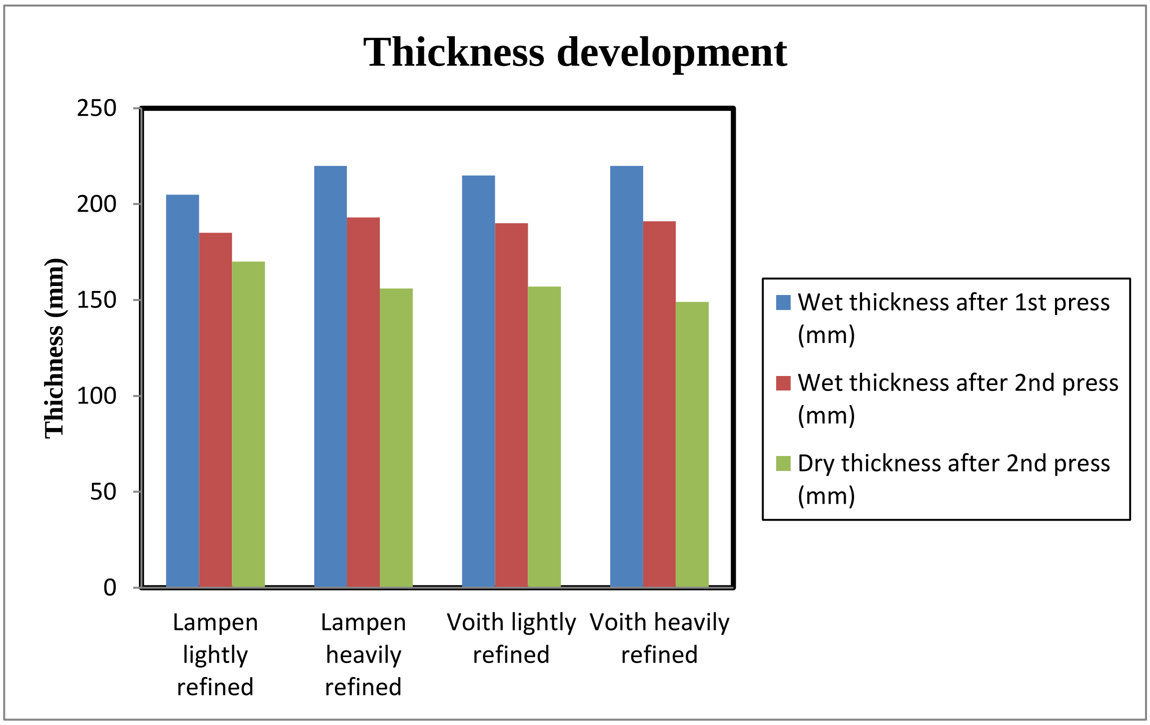
Fibre Properties						
Sample	SEC	Fibre length, mm	Content of Fines, %	Fibre Curl, %	Fibrillation, %	WRV
Unbeaten fibre		0.94	1.36	17		0.97
Lampen lightly refined	3500	0.9	2.25	13.4	0.76	1.3
Lampen heavily refined	7000	0.89	2.86	12.7	0.94	1.52
Voith lightly refined	75	0.83	3.3	14.2	1.04	1.42
Voith heavily refined	150	0.72	5.46	13	1.42	1.66

Sheet properties development

	Lampen lightly refined	95% conf.	Lampen heavily refined	95% conf.	Voith lightly refined	95% conf.	Voith heavily refined	95% conf.
DSC after forming (%)	18.49	39.20	17.71	0.21	18.09	0.12	16.83	0.10
DSC after 1st press (%)	36.73	4.36	31.76	1.08	31.68	0.33	28.60	0.23
DSC after 2nd press	48.06	1.75	43.77	1.23	44.82	0.62	39.69	0.41
Density after 2nd press (kg/m3)	517.03	33.80	575.00	24.30	562.45	20.30	594.38	20.30
Tensile index (Nm/g)	30.26	1.68	35.62	1.89	34.16	1.75	37.49	2.74
Gurley permeance (um/pa*s)	19.30	0.84	12.05	1.07	10.14	0.52	5.54	0.27
ISO brightness	84.44	0.17	83.05	0.08	83.96	0.10	82.44	0.24
Opacity	79.13	0.41	76.95	0.75	81.32	1.04	80.89	0.69
Light scatter (m2/kg	29.80	0.72	25.90	0.89	32.22	1.12	31.51	2.01

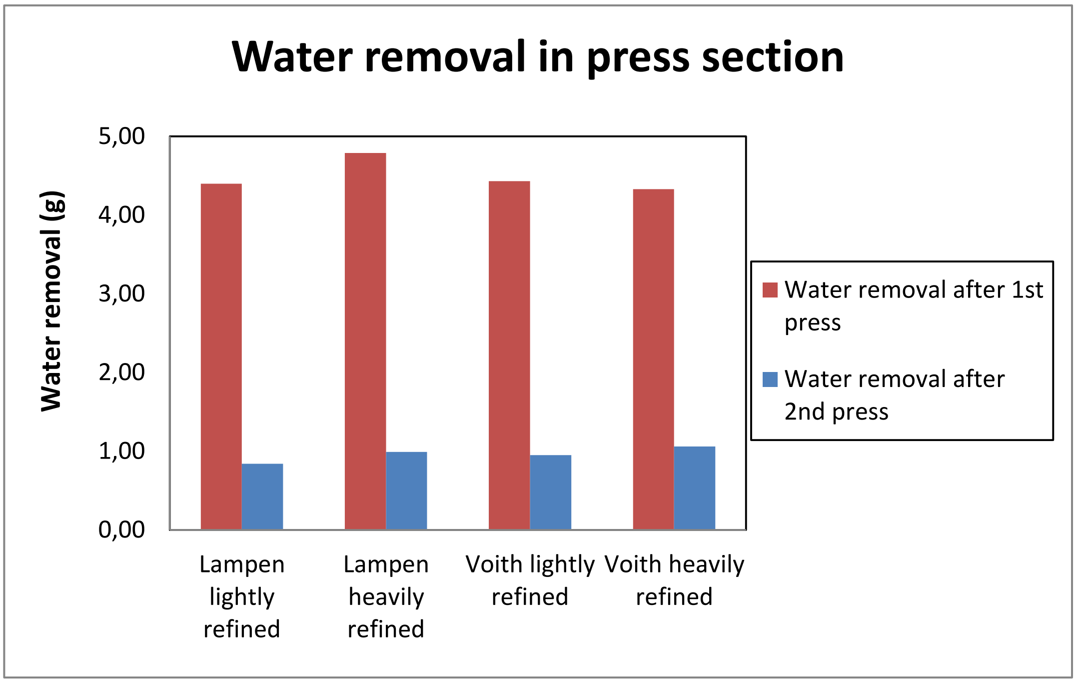
Thickness development

	Lampen lightly refined	Lampen heavily refined	Voith lightly refined	Voith heavily refined
Wet thickness after 1st press (mm)	205	220	215	220
Wet thickness after 2nd press (mm)	185	193	190	191
Dry thickness after 2nd press (mm)	170	156	157	149



Water removal development

	Water removal after 1st press (g)	95% conf.	Water removal after 2nd press (g)	95% conf.
Lampen lightly refined	4.40	0.12	0.84	0.03
Lampen heavily refined	4.79	0.11	0.99	0.06
Voith lightly refined	4.43	0.09	0.95	0.08
Voith heavily refined	4.33	0.15	1.06	0.05



Dry solid content development of no fines sample

	Lampen heavily refined without fines	Voith heavily refined without fines
DSC after forming	18,6	17,4
DSC after 1st press	35,2	32,5
DSC after 2nd press	48,3	44,8